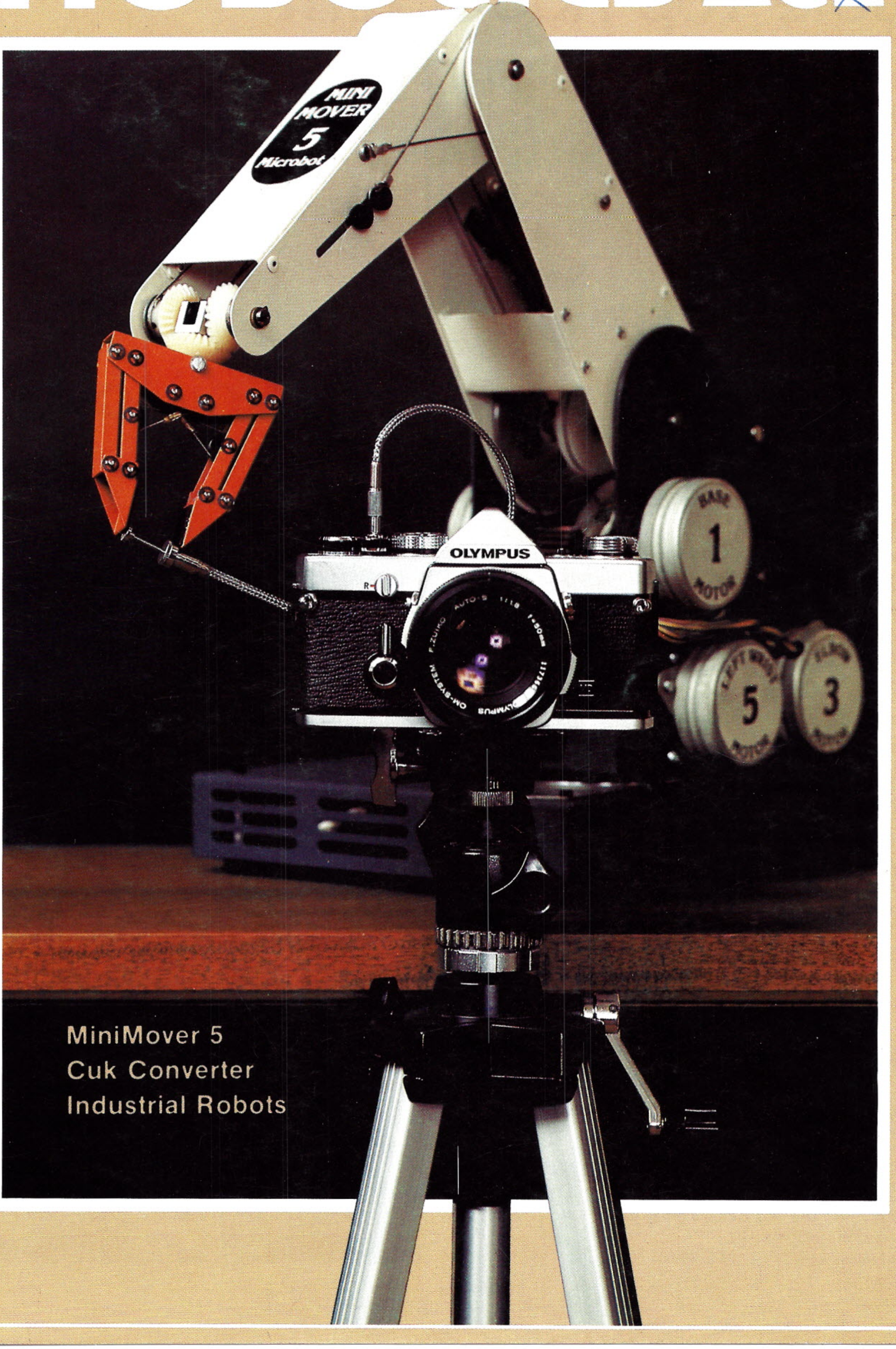
SUMMER 1980 Vol. 2, No. 2 $2.50 USA/$2.90 CANADA

ROBOTICS AGE



MiniMover 5
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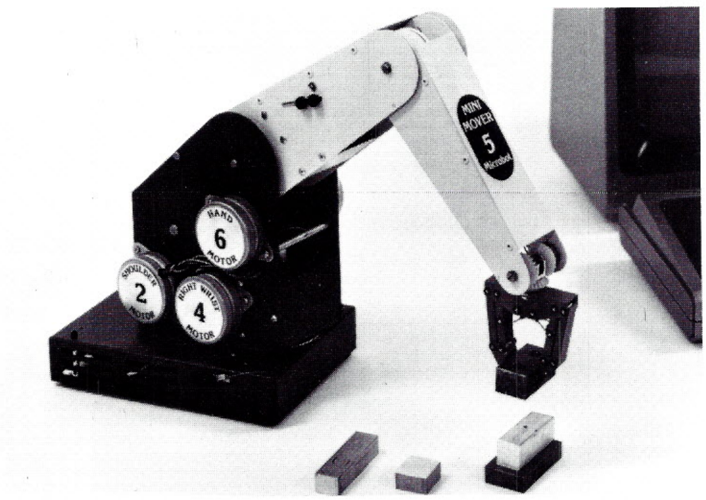

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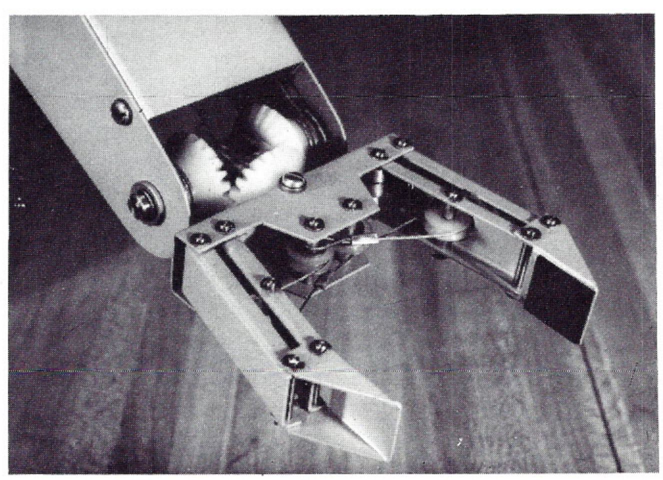

FIRST OF A SERIES

FTC Revolt

You've heard of the tax revolt. It's about time for an FTC revolt. Here's my story and why we've got to stop federal bureaucratic regulation.

My story is only one example of how the FTC is harassing small businesses but I'm not going to sit back and take it.

**By Joseph Sugarman,
President, JS&A Group, Inc.**

I'm pretty lucky. When I started my business in my basement eight years ago, I had little more than an idea and a product.

The product was the pocket calculator. The idea was to sell it through advertisements in national magazines and newspapers.

Those first years in the basement weren't easy. But, we worked hard and through imaginative advertising and a dedicated staff, JS&A grew rapidly to become well recognized as an innovator in electronics and marketing.

THREE BLIZZARDS

In January of 1979, three major blizzards struck the Chicago area. The heaviest snowfall hit Northbrook, our village—just 20 miles north of Chicago.

Many of our employees were stranded—unable to get to our office where huge drifts made travel impossible. Not only were we unable to reach our office, but our computer totally broke down leaving us in even deeper trouble.

But we fought back. Our staff worked around the clock and on weekends. First, we processed orders manually. We also hired a group of computer specialists, rented outside computer time, employed a computer service bureau, and hired temporary help to feed this new computer network. We never gave up. Our totally dedicated staff and the patience of many of our customers helped us through the worst few months in our history. Although there were many customers who had to wait over 30 days for their parcels, every package was eventually shipped.

WE OPENED OUR DOORS

During this period, some of our customers called the FTC (Federal Trade Commission) to complain. We couldn't blame them. Despite our efforts to manually notify our customers of our delays, our computer was not functioning making the task extremely difficult.

The FTC advised JS&A of these complaints. To assure the FTC that we were a responsible company, we invited them to visit us. During their visit we showed them our computerized microfilm system which we use to back up every transaction. We showed them our new dual computer system (our main system and a backup system in case our main system ever failed again). And, we demonstrated how we were able to locate and trace every order. We were very cooperative, allowing them to look at every document they requested.

The FTC left. About one week later, they called and told us that they wanted us to pay a $100,000 penalty for not shipping our products within their 30-day rule. (The FTC rule states that anyone paying by check is entitled to have their purchase shipped within 30 days or they must be notified and given the option to cancel.)

NOT BY CONGRESS

The FTC rule is not a law nor a statute passed by Congress, but rather a rule created by the FTC to strengthen their enforcement powers. I always felt that the rule was intended to be used against companies that purposely took advantage of the consumer. Instead, it appears that the real violators, who often are too difficult to prosecute, get away while JS&A, a visible and highly respected company that pays taxes and has contributed to our free enterprise system, is singled out. I don't think that was the intent of the rule.

And when the FTC goes to court, they have the full resources of the US Government. Small, legitimate businesses haven't got a chance.

We're not perfect. We do make mistakes. But if we do make a mistake, we admit it, accept the responsibility, and then take whatever measures necessary to correct it. That's how we've built our reputation.

BLOW YOUR KNEE CAPS OFF

Our attorneys advised us to settle. As one attorney said, "It's like a bully pulling out a gun and saying, 'If you don't give me a nickel, I'll blow your knee caps off.'" They advised us that the government will subpoena thousands of documents to harass us and cause us great inconvenience. They warned us that even if we went to court and won, we would end up spending more in legal fees than if we settled.

To settle would mean to negotiate a fine and sign a consent decree. The FTC would then issue a press release publicizing their victory.

At first we tried to settle. We met with two young FTC attorneys and agreed in principle to pay consumers for any damages caused them. But there were practically no damages, just a temporary computer problem, some late shipments, and some bad weather. The FTC then issued a massive subpoena requesting documents that will take us months to gather and which we feel was designed to harass or force us to accept their original $100,000 settlement request.

Remember, the FTC publicizes their actions. And the higher the fine, the more the publicity and the more stature these two attorneys will have at the FTC.

If this all sounds like blackmail—that's just what it appeared to be to us.

We did ship our products late—something we've admitted to them and which we publicly admit here, but we refuse to be blackmailed into paying a huge fine at the expense of our company's reputation—something we've worked hard eight years to build.

We're not a big company and we realize it would be easier to settle now at any cost. But we're not. If this advertisement can attract the attention of Congressmen and Senators who have the power to stop the harassment of Americans by the FTC, then our efforts will be well spent.

ALL AMERICANS AFFECTED

Federal regulation and the whims of a few career-building bureaucrats is costing taxpayers millions, destroying our free enterprise system, affecting our productivity as a nation and as a result is lowering everybody's standard of living.

I urge Congressmen, Senators, businessmen and above all, the consumer to support legislation to take the powers of the FTC from the hands of a few unelected officials and bring them back to Congress and the people.

I will be running this advertisement in hundreds of magazines and newspapers during the coming months. I'm not asking for contributions to support my effort as this is my battle, but I do urge you to send this advertisement to your Congressmen and Senators. That's how you can help.

America was built on the free enterprise system. Today, the FTC is undermining this system. Freedom is not something that can be taken for granted and you often must fight for what you believe. I'm prepared to lead that fight. Please help me.

Note: To find out the complete story and for a guide on what action you can take, write me personally for my free booklet, "Blow your knee caps off."

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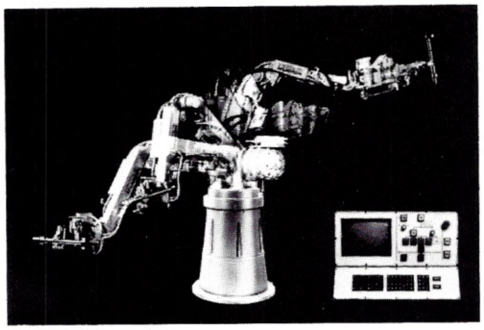

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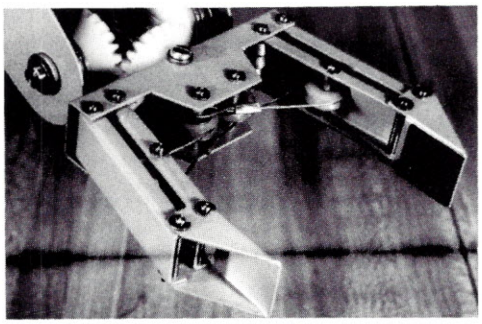

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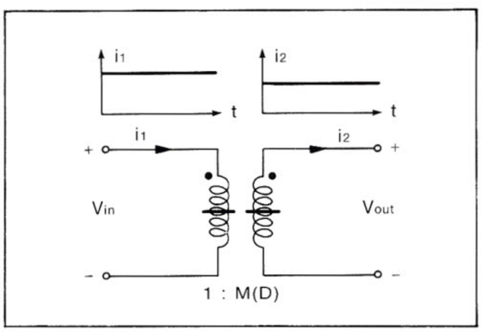

Cover photo by John R. Jones.

Articles

Departments

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LETTERS

Microcomputer Based Path Control

In my paper in the last issue of Robotics Age, I tried to present the concepts of proportional error control and the impact of differentiation and integration on such controllers. In so doing, I made rather liberal use of terminology in an effort to make the ideas clear. My friends in the control theory business are giving me a bit of good-natured trouble about one term in particular, that of a "PID controller."

Strictly speaking, the pseudo-derivative controller (PDF) I described is a *compensated derivative* controller, not a PID controller. A true PID controller has an output which is a weighted sum of three terms: the error signal, its integral, and its derivative. The two figures below illustrate the differences in form of these controllers.

To see the functional differences, we need to assume something about the load (the robot joint), and we must write a differential equation. We assume, as before, that angular velocity (w) is the controlled variable, and this time we will assume a purely inertial load. Such a load satisfies

$$T = J\dot{w}$$

where $\dot{w}$ is the derivative with respect to time of angular velocity (angular acceleration), J is inertia, and T is torque. With the knowledge that the torque output by the controller equals the torque seen by the load, we will now consider the two controllers.

For a PID,

$$J\dot{w} = K_e (w_d - w) + K_i \int_0^t (w_d - w)dt' - K_d w$$

differentiating both sides with respect to time removes the integral and yields

$$J\ddot{w} = -K_e\dot{w} + K_i(w_d - w) - K_d\ddot{w}$$

or

$$(J+K_d)\ddot{w} + K_e\dot{w} + K_i w = K_i w_d$$

Now, for a PDF,

$$J\dot{w} = \int_0^t K_i (w_d - w)\, dt' - K_d w$$

similarly, we get

$$J\ddot{w} + K_d\dot{w} + K_i w = K_i w_d$$

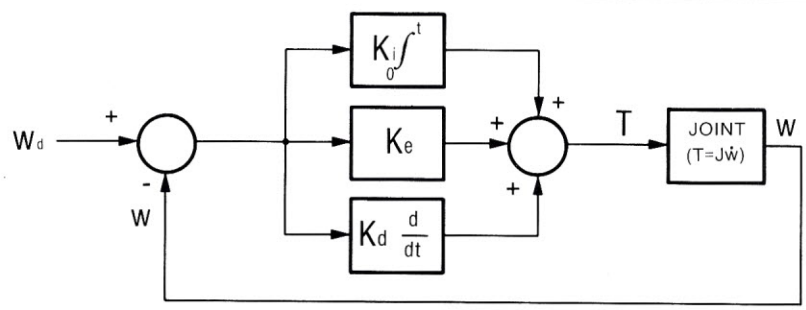
So both controllers implement a system which satisfies a second order linear differential equation with constant coefficients. And rather standard techniques can be used to find choices of K_i and K_d or of K_i, K_d, and K_e to give the desired type of response. Typically, we want a response which is as fast as possible without exceeding the "speed limit" and overshooting, resulting in a "critically damped" system.

Manipulating the differential equations in the two cases, we find that for critical damping we must choose the constants so that they satisfy

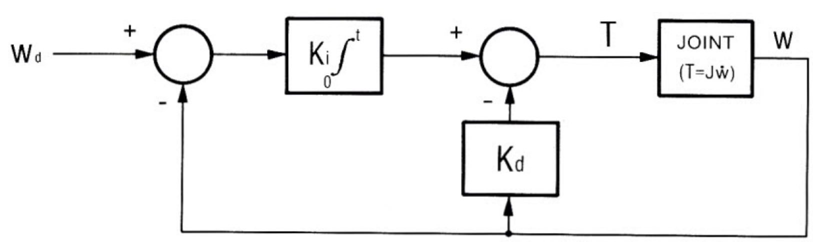
$$K_e^2 - 4K_i (J + K_d) = 0 \text{ for PID}$$

and

$$K_d^2 - 4JK_i = 0 \text{ for PDF.}$$



A PID CONTROLLER



A PDF CONTROLLER

In both cases, choices can be made which will satisfy these conditions. The designer of a PID controller can be made which will satisfy these conditions. The designer of a PID controller has somewhat more flexibility, since he has an additional variable to work with.

One more note: I said these were differential equations with "constant coefficients." To assume that the inertia term J is constant in the case of controlling a robot arm is making a strong assumption, since this is almost never true, due to changes in the arm's configuration. Obviously, this complicates the problem for either type of controller.

Dr. W. E. Snyder
DFVLR,
Wessling/Obb., W. Germany

Hardware Bias?

Editor:

I picked up your second issue the other day and was thoroughly impressed by its content. Congratulations! With any luck, and within a year, you should be monthly (or bimonthly). Where most magazines fill a need where one exists, yours is preparing to fill a need which will soon exist.

Prof. Cuk's article is one of the most straightforward and logical presentations I have ever seen on the functioning of *any* circuit. I look forward to the second half of the article.

One note and suggestion. I noticed a definite hardware approach to the articles in your magazine. I realize there are other sources for such information, but it would be nice if you included articles on software implementation of robot systems, or on general Artificial Intelligence theory as well. That would round out the magazine.

Also, some hobbyist-type robot projects would be in keeping with the tone of your magazine . . . As an amateur radio operator and professioanl programmer, I've been intrigued by the possibility of building a hobby robot linked to a home computer by radio.

S. Koren
Newark, DE

I trust that our Spring and Summer issues provide the balance between hardware/software and industrial, professional, and amateur *work that you (and others) are looking for. We will continue to cover all sides of the field, but we need to hear from more people working in each area to guarantee an appropriate balance in each issue.*

We have in the works a series on artificial intelligence techniques for robot reasoning as well as vision, which many have asked for. You will also be pleased to know that we plan a description of a system using National's new A/D transceiver chip to provide the computer/robot data link you mention.

—AMT

One of the purposes of our Letters department is to serve as a forum on robotics-related issues. Selected questions on robot design problems will be answered. We are always interested in hearing what subjects you would like to see covered in our articles. Send your comments, suggestions, and questions to:

Editor
Robotics Age
P. O. Box 801
La Canada, Calif. 91011

RE: DC Speed Control

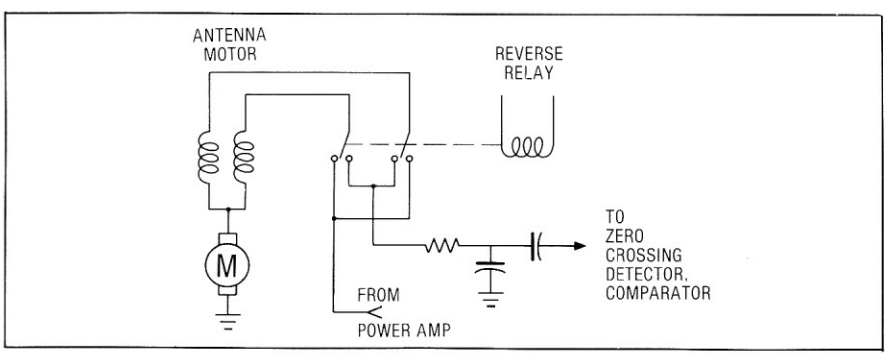
Editor:

It seems that with some motors (those used for power antennas and windows in cars), you can eliminate the encoder wheel in the phase-locked servo system in Vol. 1 No. 1. These motors have two field windings wound in opposite directions to control rotation of the armature.

By using a low pass filter and blocking capacitor, you can use the field not in use at the time as your pulse generator. Output from the unused winding of an antenna motor seems to be two volts p-p at 100 Hz, with 4 volts input and the motor barely running.

The circuit then becomes as shown in the enclosed figure.

Alex J. Kowalski, Jr.
South Bend, IN



INDUSTRIAL ROBOTS TODAY AND TOMORROW

J. W. Saveriano
BHS Machinery Company
Robotics Systems Division
16162 Beach Boulevard, Suite 308
Huntington Beach, Calif. 92647

"We can dream about rockets and the moon until hell freezes over. Unless the 'people' understand it, no dice. You worry about damned calculations, and I'll talk to the people."
—Werner von Braun

Introduction

Civilized man's first job was working the land. He designed and built tools to help him do his work. Tools were later developed into machines that made products. During the Industrial Revolution there was a dramatic shift from an agriculturally-based economy to a manufacturing-based economy. Workers moved from the farm to the factory.

Mass production techniques proved more products could be produced per person per hour if the worker was assigned to load and unload the same machine, or do just one routine of operations on an assembly line. This did increase productivity but decreased job satisfaction by tying man to a machine or set of operations. Work in manufacturing remained essentially the same, with improvements being made in the various technologies in an evolutionary manner until the advent of numerically and computer controlled machinery in the 1950's.

In the early 1960's, George Devol and Unimation Incorporated introduced the first industrial robot. The basic idea was to build a machine that was flexible enough to do a variety of jobs automatically: a device that could be easily taught or programmed, so that if the part or process changed, the robot could adapt to its new job without expensive retooling, as was the case with hard automation. It was this mating of a computer to a flexible manipulator that has helped open the door to new methods of

manufacturing.

Dr. James S. Albus, in a recent book on the effect of computers and robots, wrote, "The human race is now poised on the brink of a new industrial revolution which will at least equal, if not far exceed, the first Industrial Revolution in its impact on mankind. The first Industrial Revolution was based on the substitution of mechanical energy for muscle power. The next industrial revolution will be based on the substitution of electronic computers for the human brain in the control of machines and industrial processes." [1]

If Dr. Albus is correct about the new industrial revolution, American industry has been slow to commit to this advancement. Between 1960 and 1975, the increase in robot utilization had been slow—similar to, but lagging behind, numerically and computer controlled machine tools. However, recent advances in microprocessor technology, the increasing need to improve productivity, and the long range goal of computer-controlled, unmanned manufacturing plants have provided new impetus for industry to apply robots in manufacturing. *Fortune Magazine*, in its December 17, 1979 issue, stated, "The number of industrial robots in use in the United States has more than doubled in the past three years. The industry's sales have been growing at an annual rate of thirty-five percent. Ten years from now, sales in the United States are expected to total somewhere between $700 million and $2 billion." [2]

The rest of the industrial world is also making use of this new technology. Japan is especially aggressive in its implementation of robots: "In fact, at the end of 1977, the number of industrial robots actually operating in Japan came up to approximately 30,000. Looking toward the future, annual production in 1985 is estimated to be more than fifteen times that in 1977." [3]

30,000 robots in Japan? This figure is misleading because the Japanese include in this count simple robots similiar to the Seiko Model 700 shown in Figure 3. These types of machines have been used in Japan for almost forty years. In a paper given to the Japan Industrial Robot Association, the Executive Director, Kanji Yonemoto gave this as the general view of robot use in Japan: "By virtue of their functional characteristics enabling versatile and flexible motions, industrial robots help achieve automation of the multi-product small-batch or multi-product mixed-line production, thereby contributing greatly to the improvement of productivity.

"Utilization of industrial robots brings about a change of the production system from the 'man-machine system' to 'man-robot-machine system.' This change brings socio-economic impacts, such as the improvement of working environments and the humanization of working life, by helping promote industrial safety and advance labor quality, as well as increase returns on investment, stability of product quality, and improvement of production management..."[3]

Whether we are on the brink of a new industrial revolution remains to be seen. However, there is little doubt that computers and robots will significantly alter manufacturing in the near future. To gain a better understanding of this exciting and new technology, it is best to start with some fundamentals of robotics and then advance to robot systems.

I. Basic Robot Elements

The universality of robots has caused general disagreement on a hard definition of "robot." This explains the disparity between the statistics given on the number of robots in the United States vs. Japan. Americans are far more restrictive in their definition of robot. The word robot comes to us from the Czech word for worker. It was first used to represent an automaton in 1920 when Karel Capek, a brilliant Czech playwright and author, wrote the play called *R.U.R.* (Rossum's Universal Robots). Capek's creatures were man-like; today's industrial robots bear little resemblance to most science fiction anthropomorphic robots. Most industrial robots are little more than an arm attached to a stationary base. A few have multiple arms and some are mobile. Robots, however, are still in their first generation and will take many forms in the future.

For the purposes of this paper, we will define a robot as a machine that can be easily programmed to do a variety of manual tasks automatically. There are those who would include many other qualifications and criteria, such as a high degree of intelligence, the ability to react to its environment, more than four degrees of freedom, and so on, and many industrial robots satisfy this more restrictive definition.

The following are the three basic components of an industrial robot:

Controller

The robot controller functions as the brain and nervous system of the robot. It can be any programmable device from a rotary drum switch to a full computer. In sophisticated industrial robots, the control computer is capable of a high level of "artificial" intelligence and not only runs the robot through its programmed moves, but

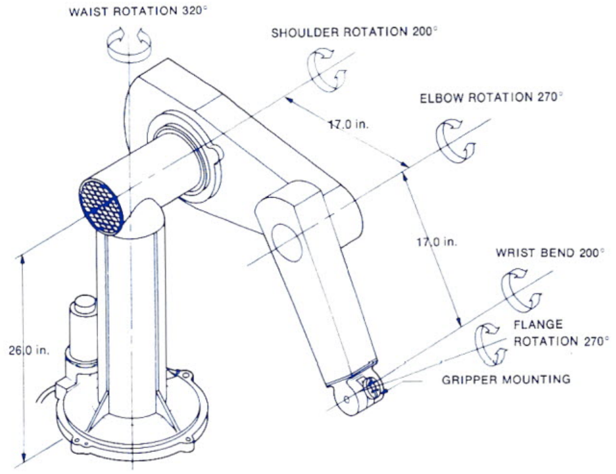


Figure 1. PUMA 500, a 5-axis, electric powered robot arm.

also integrates it with ancillary machinery, equipment and devices. The controller can also monitor processes and can make decisions based on system demand while at the same time reporting to a supervisory control. This will be covered in more depth in the section on advanced robotics.

Manipulator

The manipulator consists of the base and arm of the robot, including the power supply, usually hydraulic, electric or pneumatic. The manipulator is the component that provides movement in any number of degrees of freedom. The manipulator's movement can be described in relation to its coordinate system, which may be cylindrical, spherical, jointed-spherical, etc. Depending on the controller, movement can be servo or non-servo controlled and can be from point to point or along a specified continuous path. The robot shown in Figure 1 is a jointed-spherical, servo controlled, continuous path arm with five revolute axes.

Tooling

The hand or gripper, sometimes called the "end effector," can be a mechanical, vacuum, or magnetic device for part handling. At present, most of these devices are only two position, i.e. open/closed, on/off. Figure *2a* and *b* show two simple hands used for grabbing cylindrical parts. The fingers are easily changed to accomodate different part configurations. Figure 2c shows a gripper that holds the workpiece either by the I.D. or O.D. to facilitate loading or transfer. Figure *2d* is a double hand that also grabs the I.D. or O.D. The dual hand is advantageous because it enables the robot to unload a machine tool with one hand while holding the unprocessed part in the other. This allows the robot to reload the machine without moving back to a pick-up point to get the next part. Figure *2e* is a special gripper used in the die cast machine work cell shown in Figure 8. The lower part of the hand loads the two inserts into the die cavity. After the die cast machine cycles, the upper part of the hand unloads the cavity.

Robots are not only used for material handling; they are also very effective tool handlers. Figures *2f, g, h* and *i* show some common tools that can be manipulated by industrial robots. Figure *2j* is a quick disconnect coupling at the end of the robot's wrist so that it can change tools automatically. The variety of tools and grippers that can be adapted for robot use is unlimited.

It is, however, the gripper of today's industrial robot that is one of the most limiting factors in universal robot utilization due to the lack of hand programmability. It is the weakest link of the robot's components. Extensive research and development is being done to produce a gripper that can handle a wide assortment of part configurations.

One of the greatest lessons in the study of artificial intelligence and robotics is the recognition of the marvels of the magnificent human machine.

III. Types of Industrial Robots

As varied as the definition of "robot," there are many ways to classify different types of robots. Under the broad classification of industrial robots, categories may be based on the kind of work the robot is assigned to do, such as spray painting, welding, assembly, material handling, etc.

Simple Robots

Simple robots are also called "pick and place" devices and "limited sequence" manipulators. Simple robots are the most underrated and underutilized robots in the United States. These low cost, easy-to-maintain, fast, and accurate devices can dramatically increase productivity in medium- and long-run production industries.

Simple robots like the one shown in Figure 3 are usually very limited in the amount of information that can be stored in their memory. Generally, only sequence and time are used in their programs, although some branching and subroutines are possible with today's low cost, increasingly powerful programmable controllers.

Normally, these devices are restricted to three or four non-servo degrees of freedom. Mechanical stops are used on each axis to set the amount of travel; this is usually only two positions, i.e., up/down, right/left, in/out. Because they are very limited in the number of moves available to the manipulator, simple robots are very dependent on

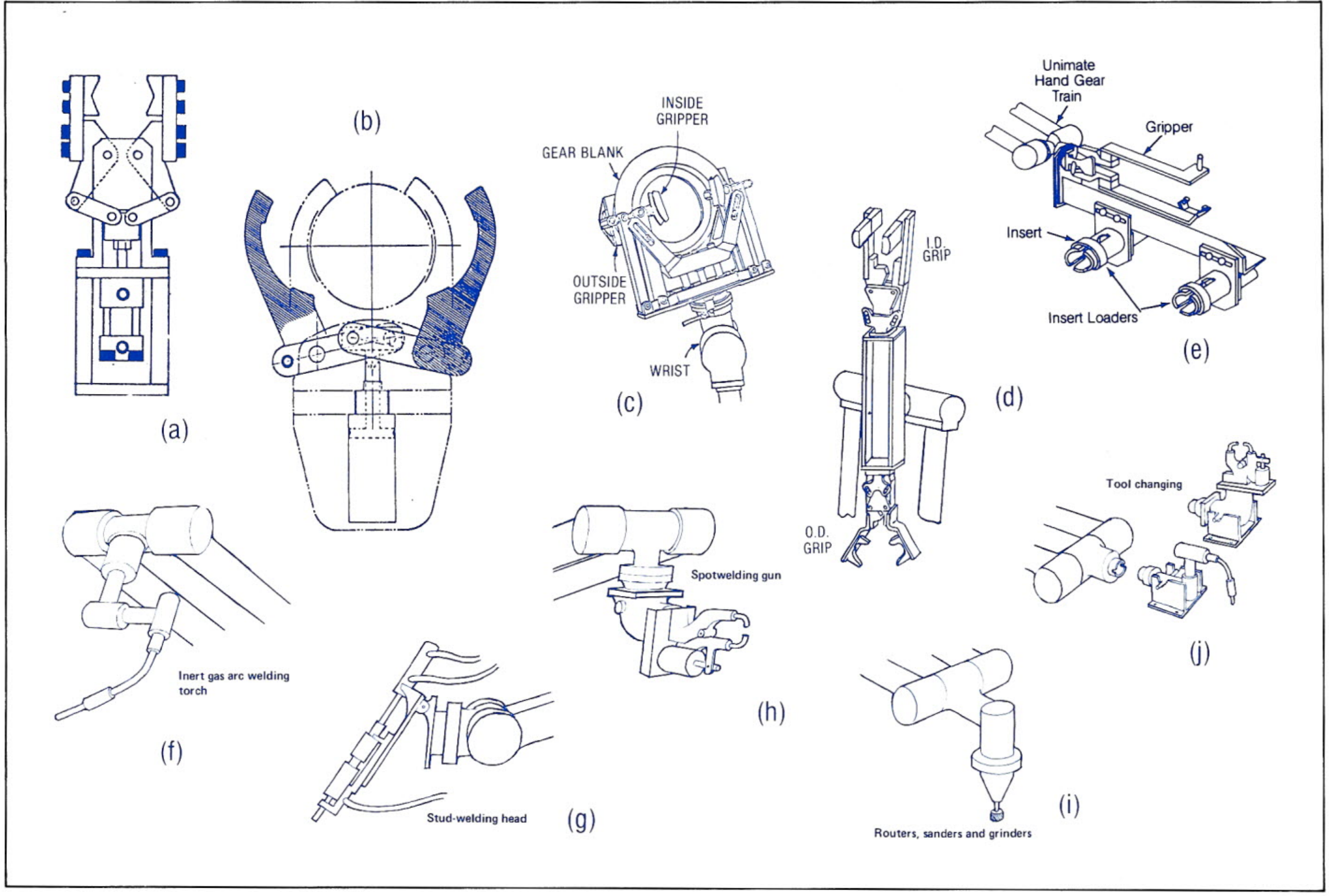


Figure 2. Assortment of robot grippers and tools.

support equipment such as bowl feeders and part presenters. A general rule of thumb in robotics is that the higher the intelligence of the controller and the greater the programmability and number of moves of the manipulator and tooling, the less dependent the robot will be on support equipment.

Simple robots usually are air-operated, accurate to ±.001″ or better, and can operate as fast as a cycle per second. These robots cost anywhere from $3,000 to $15,000.

Medium Technology Robots

Medium technology robots have a greater memory capacity and are easier to teach than simple robots. Such robots have four to six degrees of freedom and are servo-controlled in most of their axes of movement. The robot shown in Figure 4 is a good example of a medium technology robot. It has a 256 step memory and is programmable in its three major axes, i.e., waist rotation, radial traverse, and vertical traverse. The wrist bend and rotation are non-servo and set with mechanical stops as with the simple robot.

Medium technology robots are usually used in single machine load/unload-type jobs and are not capable of continuous path operations required for welding and spray painting applications. There are many jobs in manufacturing today that could be automated by using medium technology robots. Such units can cost from $15,000 to $35,000 and generally have a repeatability of ±.050″.

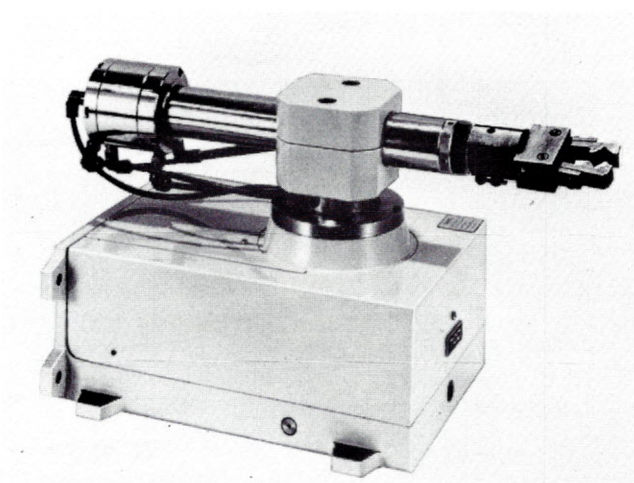


Figure 3. Seiko Model 700, a 4 axis, air-operated simple robot arm.

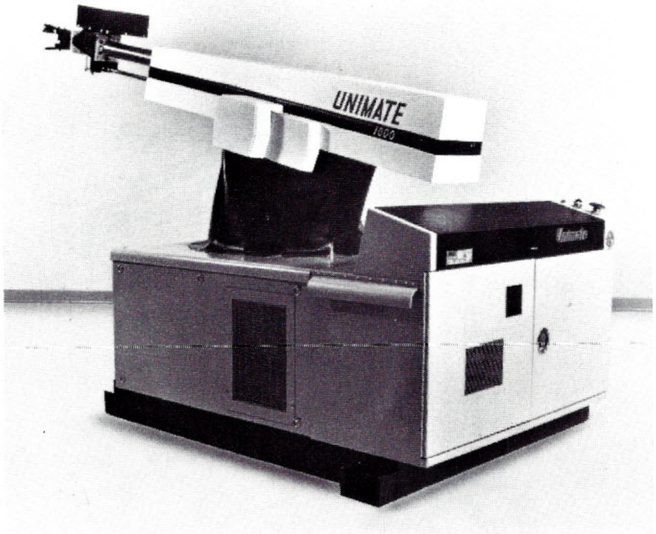


Figure 4. Unimate Model 1000, a 5 axis, hydraulic operated medium technology robot.

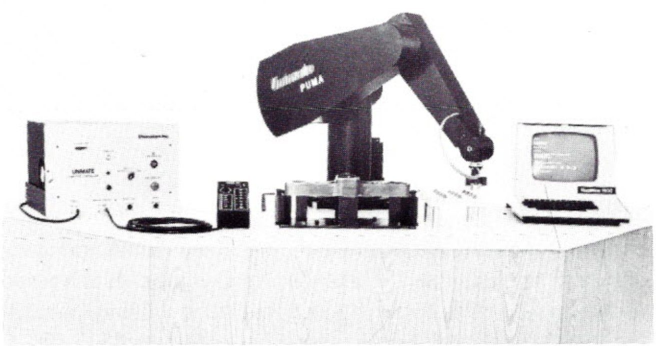


Figure 5. Unimate PUMA, a 5 axis, sophisticated robot (see Figure 1 for dimensional data). Also shown are the LSI-11 controller, teach pendant and computer terminal.

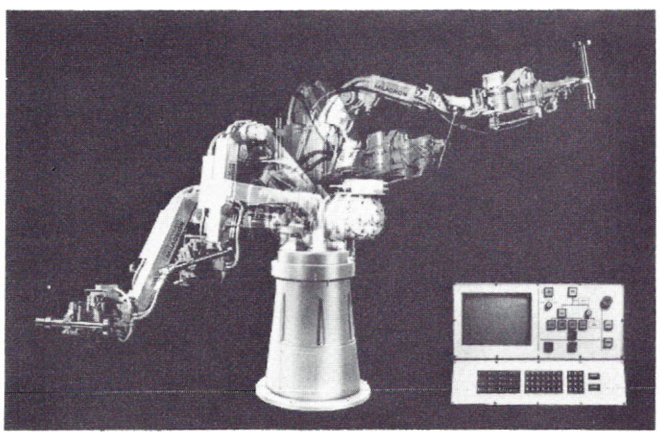


Figure 6. Cincinnati Milacron's T³ sophisticated robot, shown in various configurations by multiple exposures.

Sophisticated Industrial Robots

Sophisticated industrial robots are considered by many to be the superstars of the robot family and are at the leading edge of manufacturing technology. These robots possess highly flexible and programmable manipulators and utilize controllers that exemplify the highest level of artificial intelligence used in industrial automation. Such controllers can be interfaced with sophisticated sensory and inspection devices, and also enable the robot to be taught even the most complex of jobs with relative ease. The sophisticated industrial robot has the capability of being integrated into a myriad of computer-controlled work cells and systems.

Today's sophisticated robots, such as the PUMA arm shown in Figure 5, and Cincinnati Milacron's T^3 robot shown in Figure 6, are truly amazing tools. These machines have given computers the ability to move in space, and can be thought of as the physical extension of the computer in the real world.

Sophisticated industrial robots have a large on-board memory, capable of containing multiple programs and the ability to change programs automatically, depending upon the requirements of the work cell or system in which they are working. These machines are easily programmed by teach gun, terminal keyboard, or off-line programming, or any combination of the three. Limited voice control is becoming available. High level robot programming languages and software are being used. Sophisticated robots' controllers are usually micro- or mini-computers; program storage can be on any number of available media. The manipulators have five or more degrees of freedom and are fully programmable in all axes: these manipulators can operate either point to point or continuous path. Small sophisticated robot arms such as the PUMA have repeatability of ±.002″ carrying loads of a few pounds, larger sophisticated robots, such as Unimation's Model 2000 are repeatable to ±.050″ even when carrying heavier payloads over greater distances. Sophisticated robots cost in the range of $40,000 to $150,000 depending on configuration.

Brief mention should be made concerning the wide range of weight-carrying capacities of industrial robots—today's robots are handling parts as small as the second hand on a watch and as large as workpieces weighing a ton. Also, it is important to realize that these classifications ar relative and in fact represent a broad continuum of capabilities. As the industry progresses, robots will change classifications—today's "sophisticated" robot will be tomorrow's "medium technology" robot.

III. Examples of Current Applications

Press Loading

Figure 7 shows the layout of a simple robot loading a press. The part is fed to the robot by the part feeding equipment. The escapement device presents the robot grip with the part. A proximity switch of some kind would be built into the escapement device, signaling the robot that a part was indeed present. The robot would grasp the part and pull it from the escapement device; as it rotates toward the press it flips its grip 180 degrees, inverting the part. All the moves occcur synchronously. The arm reaches its left rotary stop then reaches in and lowers the part into the die. When the arm is with drawn from the press, the robot's internal sensors notify its controller that the arm is clear of the press; the controller would then cycle the press. The part is either dropped through the die or blown off to a chute behind the press. The blow off and the part ejection are monitored by the robot's controller. As this is occuring, the robot swings back to the part feeder and is ready to begin the next cycle.

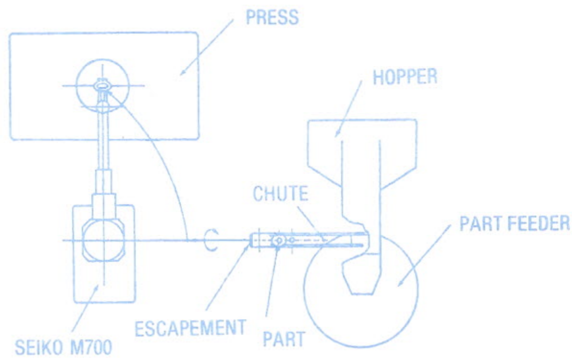
If a part jams in the feeding device or is not ejected from the die, or if any other sequence did not function as programmed, the controller would instantaneously shut down the work cell and signal the set-up man via an annunciator device.

This simple operation could be run three shifts a day, seven days a week and only require an operator to load the hopper with new parts and to remotely monitor its running. A dramatic labor savings and production increase is obvious in this kind of application, in addition to the ultimate elimination of boring, repetitive and potentially unsafe jobs which are currently performed by human operators. There is usually a reduction in scrap and die damage when automating this type of application. The simple operation just described is a good example of a basic robotic work cell.

Die Casting

Figure 8 shows a die-casting job similar to, but more complex than, the press-loading application. Die-casting is one of the most popular types of medium-technology robot applications.

A Unimate robot is shown servicing a large aluminum die-casting machine which is producing end housings for electric motors. In this job the robot does the work of one and a half human workers per shift, removing them from



the hazard of working between the dies of the casting machine and the trim press. At the same time, the output of finished housings is increased over ten percent.

This robot makes use of the special double-handed gripper illustrated earlier in Figure 2e. The robot grasps two inserts from the feed chute with one part of the gripper and then moves to the die casting machine. After unloading the previously completed shot from the machine, the gripper is swung 180° to load the next inserts, still holding the last shot. This avoids much unnecessary movement of the robot arm. The completed casting is then placed in a quench tank and a previous part is removed from the tank to the trim press. The press is open only about 8 seconds out of the cycle to unload the shot and load the two inserts. The production rate is about 160 shots per hour. [4]

Arc Welding

Welding and welding-related work is one of the areas in which the more sophisticated industrial robots have been making significant inroads. In continuous-path arc welding, for example, robots usually maintain an actual arc time of about 80%, compared to about 25% for human workers.

Figure 9 shows a complex work cell for continuous-path welding. A two-position indexer in front of each robot carries two identical welding fixtures at opposite sides of

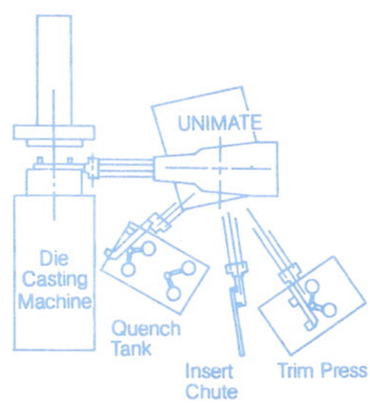


Figure 8. Medium technology robot work cell.

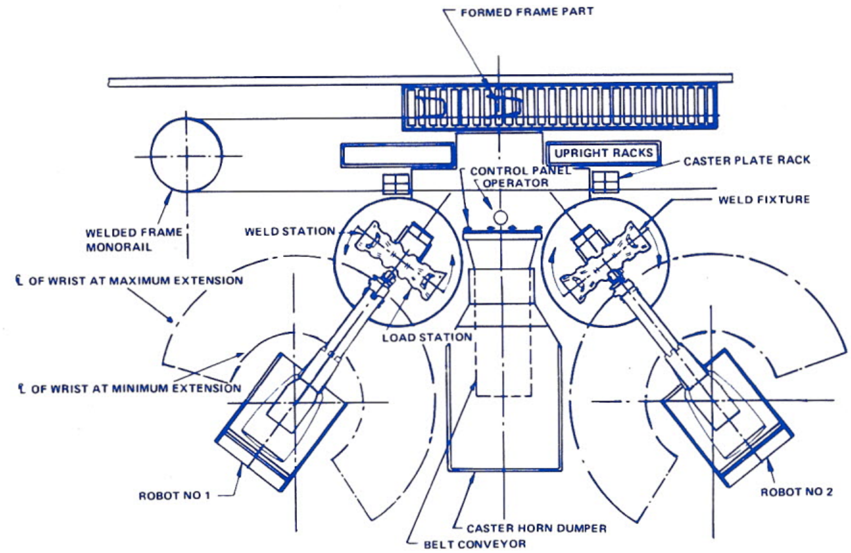


Figure 9. Sophisticated robot work cell, with two continuous path welding robots integrated into a complex work cell.

the turntable. While the workpieces in one fixture are being arc-welded by the robot, a human operator between the robots unloads the welded unit from the second fixture and reloads the fixture with the pieces for the next one.

The operator then steps to the adjoining welding station and repeats the unloading/loading operation at the indexer for the second robot. As soon as a robot is finished welding a piece, it activates the indexer, bringing the next unwelded unit into position and also unclamping the just-completed piece from the fixture.

In this application, Unimation reports that labor hours were cut to a quarter of that previously required, contributing to an 18% return on investment. Also, the welds made by the robot were regarded as having a uniformly better appearance than before automation. [5]

Another characteristic of the most advanced robots is their ability to make use of sensory information to adapt their behavior in response to changes in the work environment. In a system recently released by ASEA, Inc., shown in Figure 10, a robot operating a deburring grinder is able to follow the edge of a casting by means of a sense of touch. Unlike robots that must have the path they are to follow precisely specified in advance in their control programs, the ASEA robot automatically adapts to variations in the position or shape of the workpiece. Its sensor allows it to grind the flange down to match the actual contours of the finished product, much like a human worker who can see the results of his actions. Other robots currently under development use a touch sensor in conjunction with adaptive control to grind away welding beads by following the bead and "feeling" the actual contour of the workpiece.

These few examples of typical robot applications illustrate many of the fundamental elements of a basic robot work cell and the capabilities of various categories of robots. The first application showed a simple robot in a one-to-one relationship with the press and part-feeding equipment. The second showed a medium technology robot doing several operations in a multiple-machine work cell. The third application showed two sophisticated continuous-path robots integrated into a work cell containing conveyors, welding equipment, automated rotary tables and fixtures, all under the supervisory control of a human operator.

The following is a list of some of the benefits resulting from the appropriate application of robot technology: [6]

Increased productivity. Productivity gains ranging from 10% to 67% have been reported. No slowdown in production on second and third shifts. Uptime as high as 98%, usual with robots, means better utilization of capital equipment. The increased speed of robots also permits realizing the full potential of the high-speed machines they service.

Improved product quality. Once properly taught to perform a task, a robot will continue to do so repeatedly and consistently, meaning fewer rejects and less scrap. Users have reported improvements in quality control ranging up to 70%.

Flexibility. Unlike "hard" automation, which requires tremendous overhead in tooling for product changes, robots can be retaught and reassigned to many varied tasks. A robot's gripper and tooling can be changed quickly and easily, and almost any reasonably intelligent person can teach a robot its new task in a matter of hours.

Precision. Robots move with speed and ease, yet can also place their hands and tools with great accuracy. Repeatable positioning within .008" is common, and Unimation's new PUMA robot has a repeat of accuracy of within

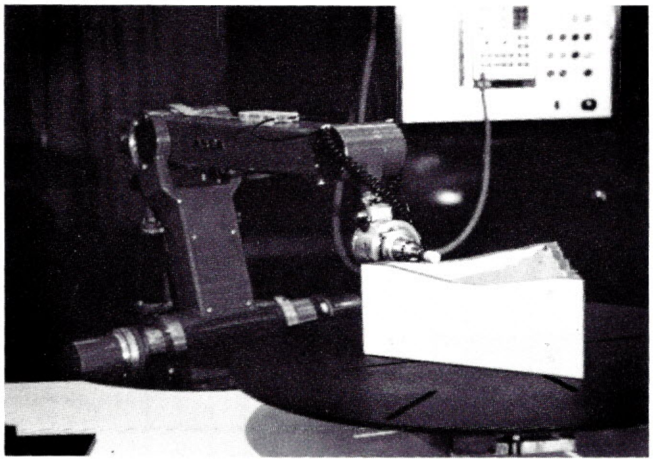


Figure 10. An advanced robot by ASEA, shown operating a deburring tool. The robot uses a sense of touch to follow the actual contour of the workpiece.

.004″.

Improved morale. It is frequently reported that workers who supervise or work with robots take a new pride in their work and in the progressiveness of their employer. Also, those who have been relieved of dangerous, tiring, boring, dirty, hot, noisy, or otherwise unpleasant "hump" jobs often experience a resurgence of pride, dignity, and a sense of loyalty to their company.

To all this are added lower indirect and hidden costs resulting from reduced inventories, longer life from tools and dies, lower average absenteeism in the human workforce, and lower costs for OSHA compliance.

IV. Advanced Robot Systems

Robot work cells of the sort described above are the basic building blocks of the automated factory. Work cells are linked together to form a "line," along which the processing of workpieces progresses from one step to the next. The result is a flexible, integrated robotic manufacturing system. The link points between the work cells usually incorporate a buffer storage unit of some type to provide some degree of isolation between the cells, permitting shutdown of a work cell for scheduled or unscheduled maintenance or setup of a new process without shutting down the entire line. Work cells "upstream" would continue to process parts and feed the storage unit serving the inoperative cell. The next cell "downstream" would continue to draw parts from its own storage unit. This filling and depleting of the storage units would be monitored by a supervisory control computer which can tune each work cell's throughput to optimize the output of the entire line.

Such a robot system can be used to manufacture a family or "group" of parts. This concept is known as *group technology*, and basically categorizes the parts into families that are of similar size, configuration, and require similar processing. As the computer becomes more widely used in manufacturing for scheduling, inventory and production control, the work flow of a system will become more efficient and it will be easier to identify the families of parts. Even without using robot systems, dramatic improvements in work flow can be obtained by using group technology. Recent studies have shown that most parts spend up to 90% of the time on pallets, in bins, or being trucked around a plant. Compare that with the continuous work flow made possible by the automated robot processing line, in which the parts are transferred directly from one manufacturing step to the next.

By applying group technology through computer-controlled machinery and robots, manufacturers begin to approach the next higher step in automated production called *Computer Aided Manufacturing*, or CAM. The U.S. Air Force is currently sponsoring research and development leading to "Integrated CAM" (ICAM). The basic idea of the study is the development of flexible computer-controlled manufacturing cells linked to other cells, forming automated manufacturing lines with a broad range of capabilities. It is believed that CAM and ICAM will significantly alter batch-type manufacturing by the early and mid-1980's. [7]

The hardware for these systems will be made up of computer-controlled machine tools and robots linked to other cells, The cell controllers will in turn be linked to each other and to system controllers, as shown in Figure 11. This arrangement of computers into such a system is known as *hierarchical control*. The fact that data is gathered and processed for control and monitoring purposes throughout this network has also ledto use of the term *distributed intelligence*. The use of these techniques will make possible the goal of fully integrated control of manufacturing facilities. [8]

In related studies, Westinghouse Electric Corporation and the National Science Foundation are participating in a $1.8 million program to research and develop a computer-controlled robotic assembly system for the batch manufacturing of electric motors. When giving reasons for the study, Richard Abraham, Westinghouse manager of programmable automation, said, "The average annual increase in productivity from 1960 to 1977 is only 2.8 percent in the United States, while it is 8.4 percent in Japan and 5.7 percent in West Germany." NSF representative Richard Green said that "...unless robotic projects are successful, the nation risks losing labor-intensive manufacturing to countries where wages are lower." [9]

It is for the above reasons that American labor has, in

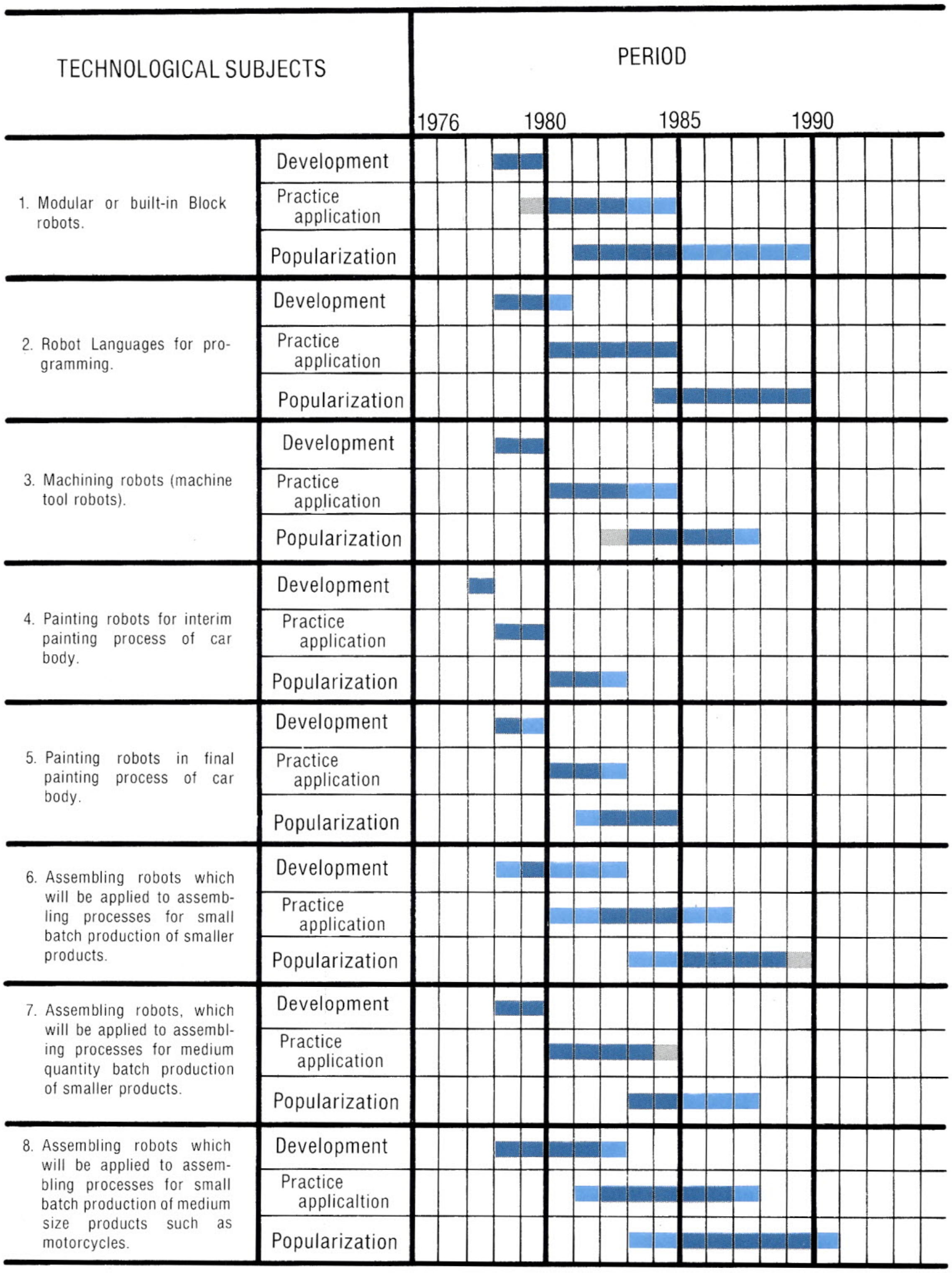
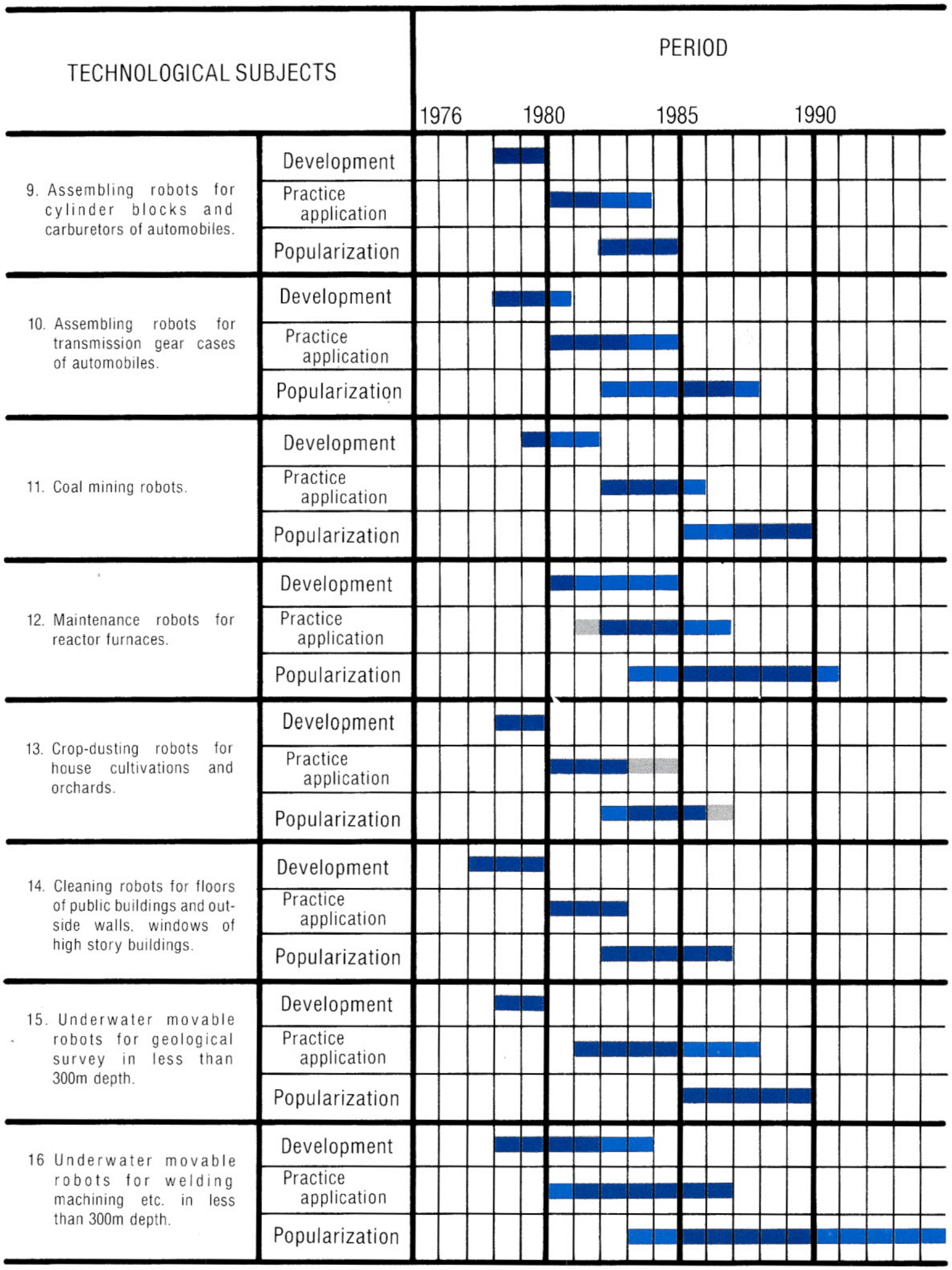


Table I. A Delphi-method forecast, conducted in 1976 by the Japanese Industrial Robot Association, predicted the technological development of industrial robots and their application in a variety of areas. The results of the first



questionnaire (shown in blue) predict the periods of development, initial application, and widespread use in each of the areas. A second group of respondents, given the first results, produced a second set of predictions in the same areas (shown in grey).

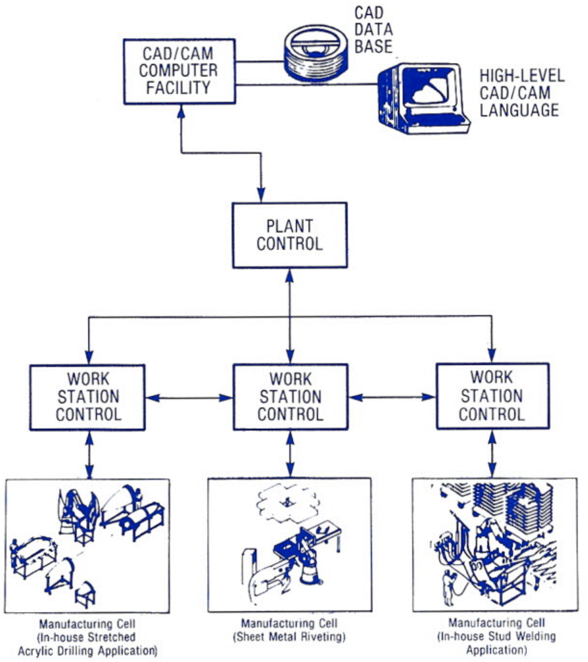


Figure 11. Advanced robot work cells, each under the control of their own computer, may in turn interact with other cells, under the control of a central plant computer. The plant controller may in turn communicate with CAD facilities.

general, supported advancements in computer-controlled robotic systems. In a recent paper stating labor's view of robots and other forms of automation, Thomas L. Weekley, International Representative, The United Automobile, Aerospace and Agricultural Implement Workers of America, said:

> The UAW membership as a whole does not currently place a specific emphasis on robots. Rather, it views robots as just one of the technological advancements facing the union today. In general, the membership has favored the introduction of such advances and has recognized them as essential in promoting economic progress through increased productivity. Further, labor as a whole has accepted and encouraged these changes.
>
> Not only does increased productivity mean additional benefits to management but employees recognize that their wages, working hours, fringe benefits, and safety will also improve as productivity increases. Productivity, therefore, is a recognized and accepted necessity for advancement of personal and corporate goals. The demand for quality low-cost goods makes increased productivity essential for economic progress.

Mr. Weekley concluded with the sobering comment that:

> Automation has the potential to benefit all of society by increasing productivity and by relieving humans of dangerous or undesirable jobs. Automation also has the potential to cause economic hardship for workers whose jobs are directly affected and eventually for others through its effect on overall employment. Therefore, a sense of security of workers and a sense of obligation by employers is a must for the successful implementation and acceptance of technological advancements. [10]

V. Future Developments

> *Listen though to the sufferings in mortals— how I found them all helpless at first, and made them able to reflect and use their wits...and then I found for them the art of using numbers, that master science, and arrangement of letters, and a discursive memory...I was first to bring the beasts to serve under the yoke and saddle, that they might take on themselves the greatest burdens of mortals.*
>
> *—Prometheus*

By the mid-1980's Japan and the United States will have computer-controlled, automated manufacturing plants using industrial robots. Human workers will perform maintenance, technical and supervisory functions. If these plants prove to be successful, they may indeed be the beginning of a new industrial revolution—an era of automation, where man is unbound from the machine to which he has been tied since the first industrial revolution.

For these plants to be successful, improvements will be required in computer hardware and software, robotics, inspection devices, sensory devices, and system design and integration. All of these elements are in existence today and rapid advancement in each of the technologies is being made. We will touch on each of these elements to provide a basic conceptual understanding.

"Artificial Intelligence is the branch of computer science devoted to programming computers to carry out tasks that if carried out by human beings would require intelligence." [11] Artificial Intelligence is known as AI. Even though this paper is about industrial robots, it is AI that will make everything we've discussed possible. The robot is primarily a manipulator controlled with AI; without AI the robot would be just another machine, and the mechanical technology to build such a device has been

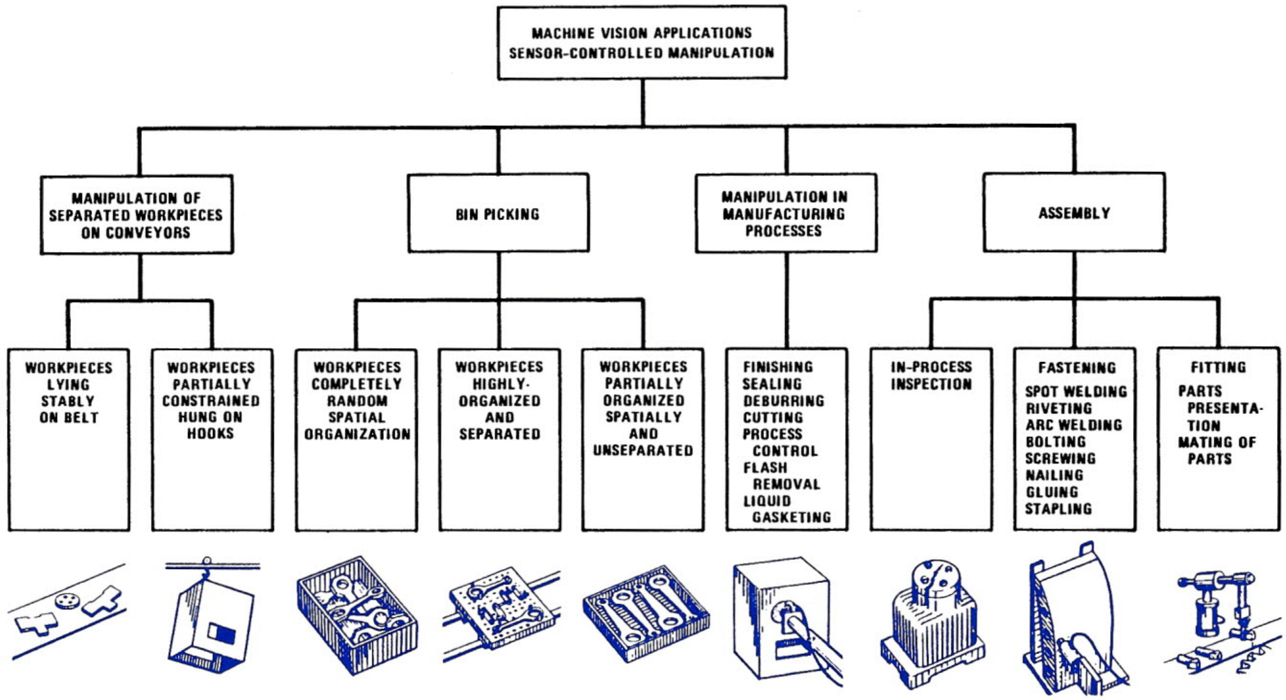


Figure 12. Block Diagram of potential vision applications in robotics. [12]

with us since the 1940's or longer. AI is important to every facet of robotics, from the teaching of the machine to the control of an entire plant. Machine Intelligence is required for the robot to remember its program, for the robot arm to know in what position its joints are in relation to itself, the workpiece and the other equipment with which it is working. AI is needed for the interfacing and communication internal and external to the robot and the system. Whether a machine can possess "real" intelligence, or the related argument whether computers can think or not, is beyond the scope of this paper. It is enough that microprocessors and their related data processing devices enable robots to follow a programmed routine and if need be make alterations to the routine based on information from its system controller or its peripherals.

Sensory devices provide information to the robot or work cell controller. Sensory devices are mounted internally within the robot to provide feedback information on arm position, tactile, force, torque, heat and other sensorial data. External to the robot a nearly unlimited amount of devices can be interfaced with the robot to provide required information on the workpiece, environment, process and ancillary equipment. Inspection devices function as quality controllers. The sensory and inspection devices form their own distributed intelligence network similar to the larger system of hierarchical controls.

Vision is man's most valued sense. It will play an important role in freeing the robot from its dependence upon support equipment as described in the simple robot section of this paper. It will add a whole new dimension to robotics. Exciting R&D work has been done on Machine Vision by organizations such as SRI International's Artificial Intelligence Center. By using solid state TV cameras and computers, scientists are now providing robots with "eyes," greatly extending the industrial robot's ability to function in the real world of manufacturing.

Figure 12 is a block diagram showing the many applications where vision will assist robots and was prepared by SRI's Artificial Intelligence Center. [12] Figure 13 shows a block diagram and data path drawing of a visual-servo control system provided by SRI.*[13] Figure 14 shows a more complex system integrating two industrial robots (one simple, one sophisticated) with an x-y table, part presenter, TV camera and other sensory devices. [14] Vision modules like the one shown in Figure 13 are now available to industry and are being used for production.

Computer Aided Design (CAD), along with Computer Aided Manufacturing (CAM), are growing in use.

> Engineers, architects, and scientists are now able to use the computer as a design tool to sketch objects in three dimensions. In the future it will be possible to connect together computer-aided design equipment with computer-controlled machine tools. This will make it possible for an engineer to design a part on a computer terminal in his office. When he is

**Editor's Note: This system was described and shown in operation in "Industrial Robotics '79" in ROBOTICS AGE, Vol. 1, No. 1.*

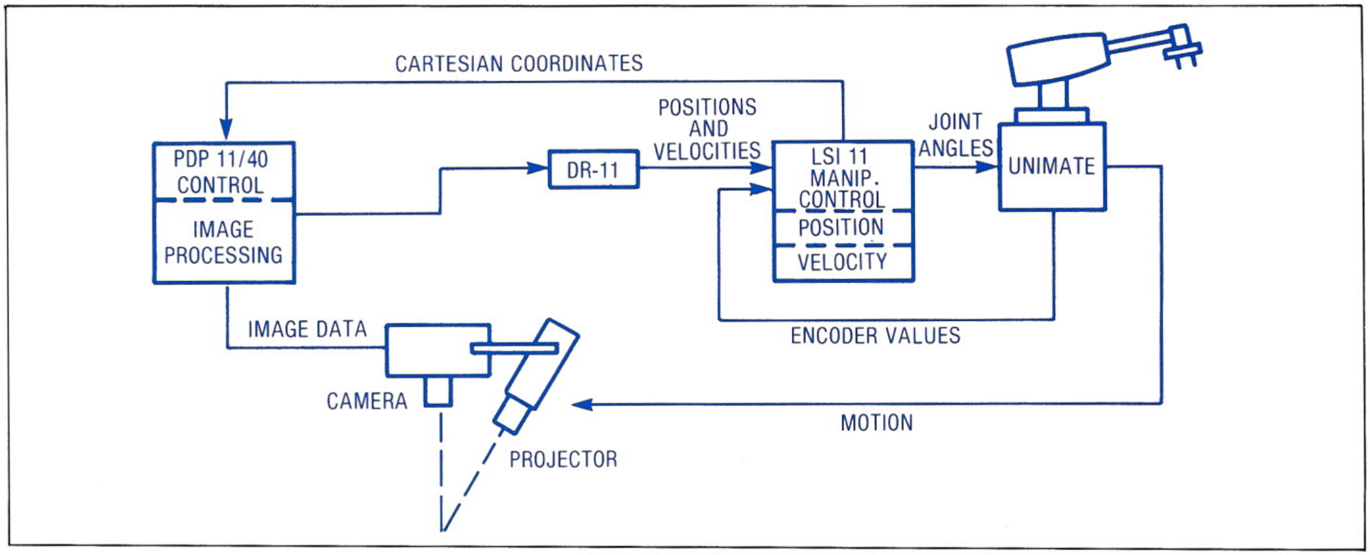


Figure 13. Block diagram of visual-servo control system. [13]

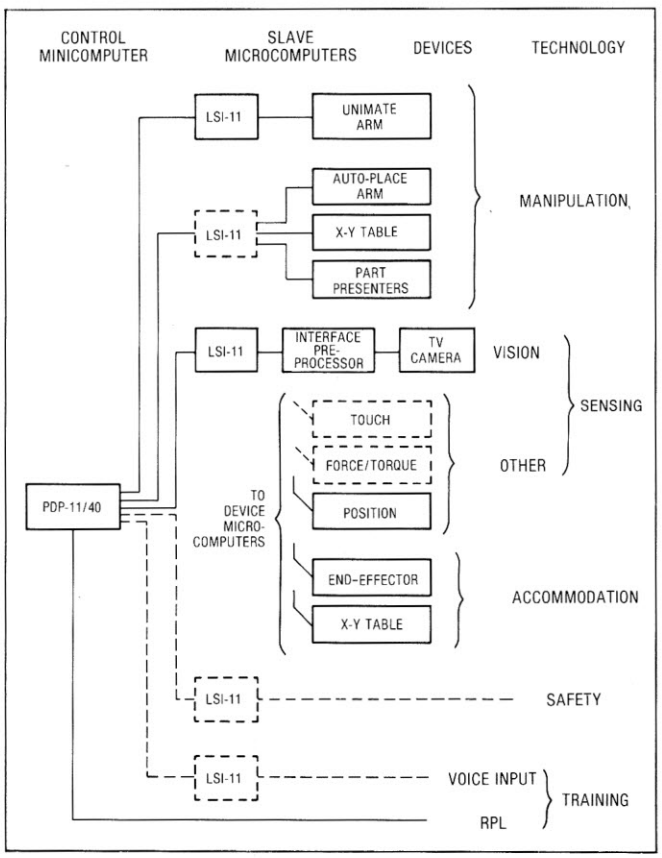


Figure 14. Block diagram of distributed computer system for robotic sensing and feedback. [14]

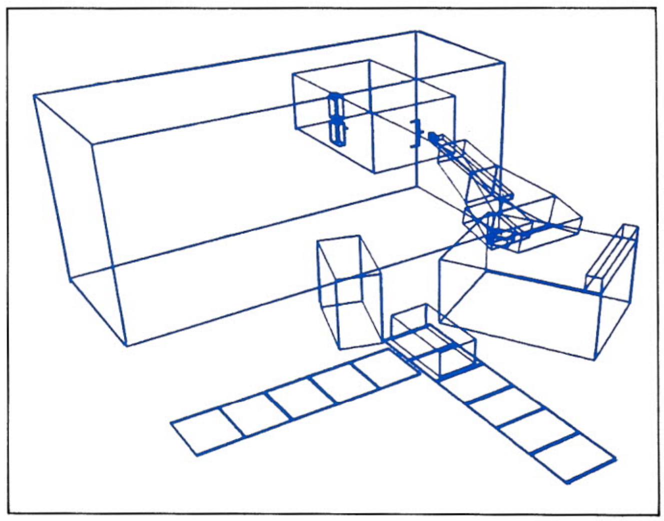


Figure 15. Example of interactive computer graphics used to lay out a robot work cell. [15]

satisfied with the design, he will be able to push a button and cause computer-generated control signals to be transmitted to an automatic machine tool, perhaps many hundreds of miles away, where the part will actually be produced without further human intervention. [1]

Computer Aided Design is also being used to build mathematical models of robot work cells to help engineers

analyze system layout and production rates. This saves enormous amounts of engineering and design time. It also reduces the need to do expensive mock-ups of the task. Figure 15 is an interactive computer graphic drawing of a robot/injection moulding work cell layout. [15]

As mentioned earlier, all the future developments we've covered are already being used by industry—or are being tested in laboratories. What about in the more distant future? What kinds of robots and computers will man be using? Because of the increasing rate of change in these technologies, even the most adventurous experts in the field are hesitant to forecast future developments any further than five or ten years. However, studies have been made by the Society of Manufacturing Engineers in this country and by the Japan Industrial Robot Association. Table 1 shows the graphic results of a 1976 JIRA study. Most studies of this kind tend to be conservative, and technological growth is projected as being linear. But what may occur may be synergistic exponential growth, with advances in computer technology beyond our greatest expectations.

Conclusion

> *Why does this magnificent applied science, which saves work and makes life easier, bring us little happiness? The simple answer runs: because we have not yet learned to make sensible use of it.*
>
> *—Albert Einstein, 1931*

Man's first tools were used to work the earth. Man's new tools will be used to work the universe. The computer and its mechanical appendage, the robot, have enormous potential to improve the welfare of mankind, but like all tools, they must be used wisely.

Technology consists of tools and techniques. To function properly the tools must be well-designed, well-built, and wisely applied. It is we, the tool builders and users who are responsible for the results of our use of technology.

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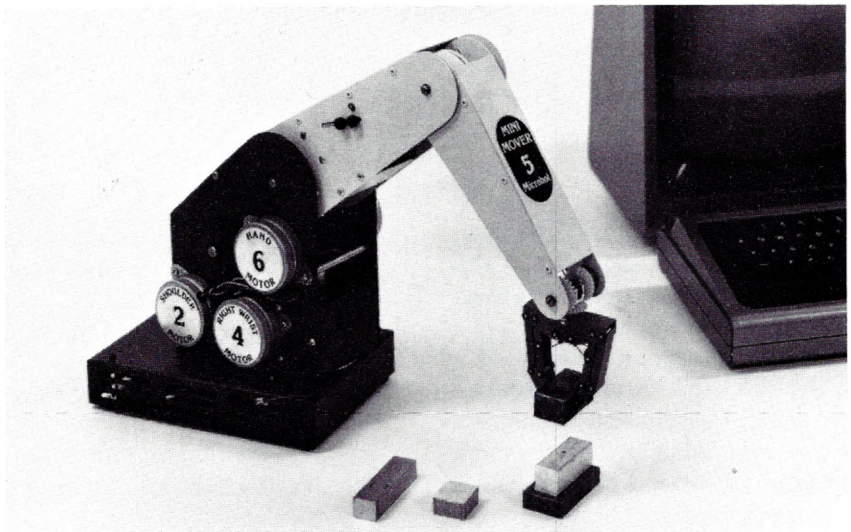

INTRODUCING MINI MOVER 5

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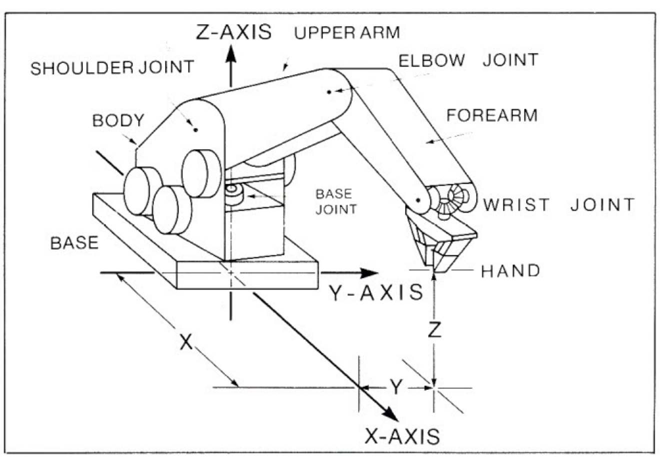


Figure 1. Major structural components. Note that a Cartesian coordinate reference frame is superimposed. The origin of this frame is where the centerline of the base joint meets the tabletop.

At the Fifth West Coast Computer Faire, held in San Francisco March 14-16, 1980, Microbot, Inc. introduced a new table-top robot arm. For a relatively low cost, the mechanical arm, its computer interface, and supporting software permit almost any microcomputer owner to get started in robotics without the effort of designing and building his own manipulator system. This versatile unit will prove useful to industry for robot evaluation as well as other light applications. Here now is a discussion of the design and operation of the Mini Mover 5, as told by its designer.

Previously, work with advanced computer-controlled manipulators was limited to laboratories at a few research oriented-universities in the US and abroad. This research has concentrated on languages for robot control and programming, computer programs that plan their own manipulation strategies, methods of efficiently performing

complex coordinate transformations, the use of sensory feedback to improve performance, and the study of manipulator kinematics. Typically, this work relies heavily on mathematical analysis, and requires highly sophisticated computing systems. Reference [1] provides a fairly complete survey of the work currently being done in these areas.

With the introduction of computer control to modern industrial robots, the results of this research are now becoming available for application in the factory environment. [2] Nevertheless, these complex new robots are still designed as heavy duty industrial equipment. Their price range, from $35,000 to $120,000 tends to hinder their use in robot experimentation by individuals and schools, as do the carefully guarded proprietary hardware and software details of these machines.

For two years, Microbot has been developing a low-cost manipulating system so that both amateur robotics enthusiasts and others could participate in this exciting field with a modest budget. The objective has been to provide a complete package including the arm, computer interface, software subroutines for coordinate conversions and control, and a high-level robot programming language, so that the user would not have to undertake a major development effort to put the unit in operation. The remainder of this article give a brief overview of the design and operation of the Mini Mover 5 as well as some typical methods of applying it. Readers interested in more technical detail will find it in the Mini Mover 5 Reference and Applications Manual [3].

Arm Mechanical Design

The arm consists of a stationary base and four movable segments connected in series by the base, shoulder, elbow, and wrist joints. The major structural components are illustrated in Figure 1. Implementation of the wrist joint is accomplished by a differential gear mechanism which can rotate the gripper in both pitch and roll. The resulting five degrees of freedom permit combined motions of the body, shoulder, elbow and wrist to position the arm anywhere from close to the base to 17.5 inches away, as shown in Figure 2. The configuration of these joints defines the position and orientation of the gripper within a partial sphere with a radius of 17.5 in. (444 mm).

The arm members are hollow, formed from folded aluminum sheet metal. The three outer segments are joined by hinge shafts that define the axis of the joint. Each joint is controlled by a flexible cable that runs from a drive unit mounted on the base to a pulley mounted on the joint shaft. Cable drive was selected because it is lightweight, highly efficient, and permits all the drive motors to be mounted on the body. This keeps weight out of the extremities, resulting in greater payload capacity.*

The shaft of the base joint is hollow, so that the drive lines for each of the motors can be brought from the interface card contained in the base of the arm. Since the axes of the three outer joints are parallel, mounting the drive motors on the body instead of the base eliminates the complications of routing the drive cables for the outer segments through a rotating joint.

The drive unit for each joint consists of a stepping motor, reduction gearing and a cable drum. From each drum, a tensioned cable goes out over pulleys to the member being driven and then returns to the drum. Rotation of the drum causes rotation of each member in proportion to the ratio of the diameter of the drive pulley attached to that member to the diameter of the drum.

The arrangement of cables used in the Mini Mover 5 is shown in Figure 3. Since the cabling design was made to simplify the geometry and maintain a low cost, several of the joints interact. Movement of one joint may result in

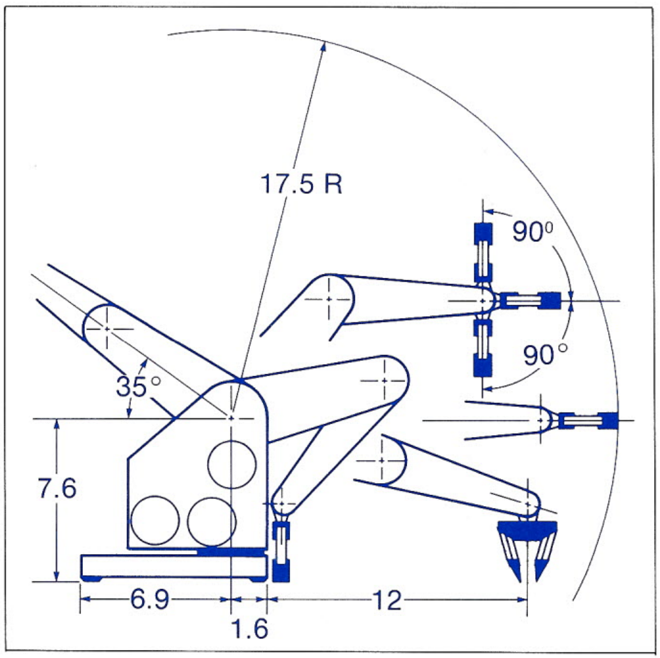


Figure 2. Mini Mover 5 working envelope.

Editor's Note: For descriptions of two other cabie-driven manipulators and related design issues, see the article "Robotics Research in Japan" in the Winter 1979 issue of ROBOTICS AGE, Vol. 1, No. 2.

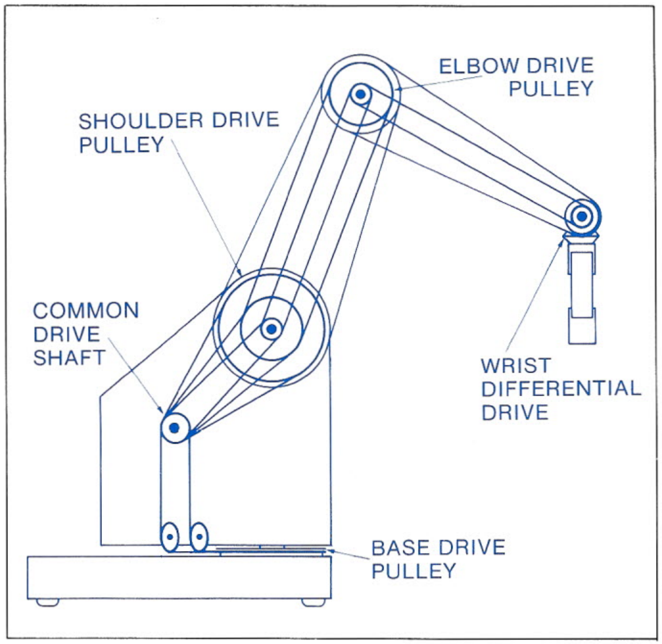


Figure 3. Cabling diagram.

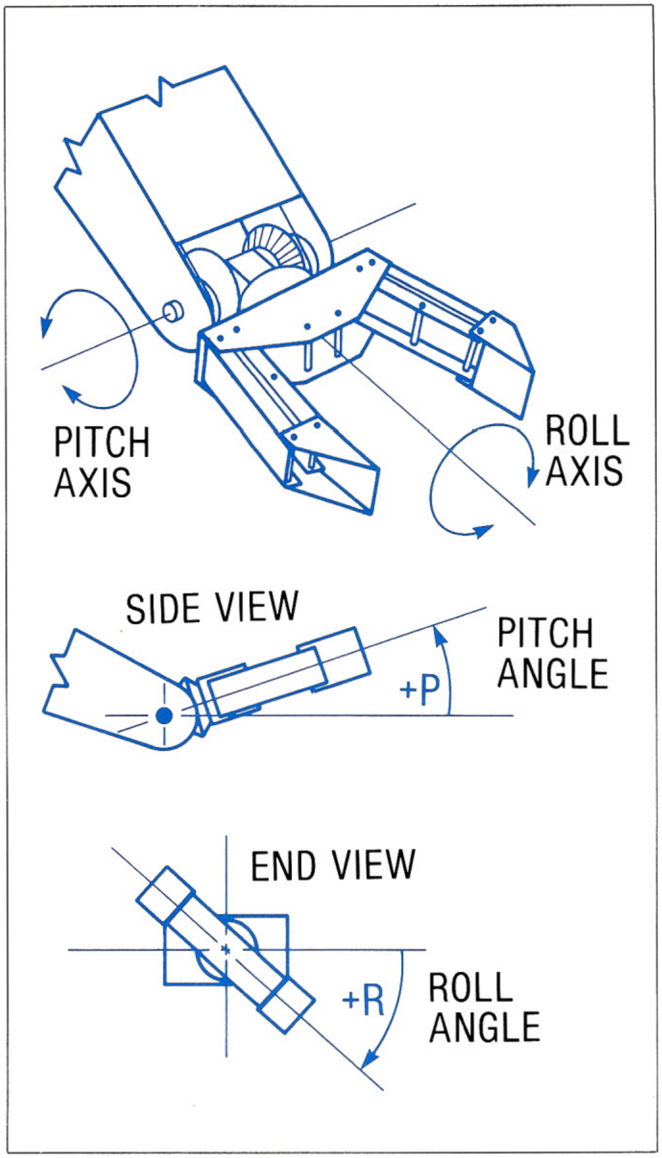


Figure 4. Definition of Roll and Pitch angles. All other joint angles are measured from the X axis.

possibly unwanted motion in another. Compensation for these interactions can be made in software. Thus, the cabling details must be understood in order to properly control the motion of the arm. As explained below, these interactions have been carefully designed so that in most cases they actually simplify the control problem.

Base Rotation (Joint 1)—The base drive cable passes over two idler pulleys, making a 90 degree bend, to a drive pulley fixed to the base. The base drive motor causes the entire arm to rotate about the base joint.

Shoulder Bend (Joint 2)—The shoulder drive cable passes around the drive pulley on the upper arm segment to rotate it about the shoulder joint.

Elbow Bend (Joint 3)—The elbow drive cable passes around an idler pulley on the shoulder axis to a drive pulley fixed to the lower arm segment. Joints 2 and 3 interact, so that changing the shoulder angle results in an equal change in the elbow angle. This interaction has been designed so that the elbow drive, in effect, controls the angle of the forearm with respect to the horizontal. However, the limits of forearm motion are measured with respect to the upper arm, not the horizontal (x-y) plane.

Wrist (Joint 4, left and Joint 5, right)—The fourth and fifth drive cables pass around idler pulleys on both the shoulder and elbow joints and terminate on the drive pulleys of the left and right wrist differential gears. The interaction of these joints with joints 2 and 3 has the effect that the wrist drives control the angle of the hand with respect to the horizontal (pitch) and the rotation of the hand around its pointing vector (roll) as shown in Figure 4. Through the action of the differential, the pitch angle P equals the average of the positions of the left and right gears and the roll angle R is their difference. The range of motion is limited to ±270 degrees at each of the wrist gears due to limits of the cable length and to ±90 degrees in pitch due to interference from the lower arm.

Hand (Joint 6)—The hand drive cable passes over idler pulleys located on the shoulder and elbow joints, through the center of the wrist differential, and finally terminates at the hand. This drive interacts with joint 3 (elbow) in that elbow bend will cause the hand to open slightly. This can be compensated for by closing the hand exactly the same number of steps that the elbow is raised.

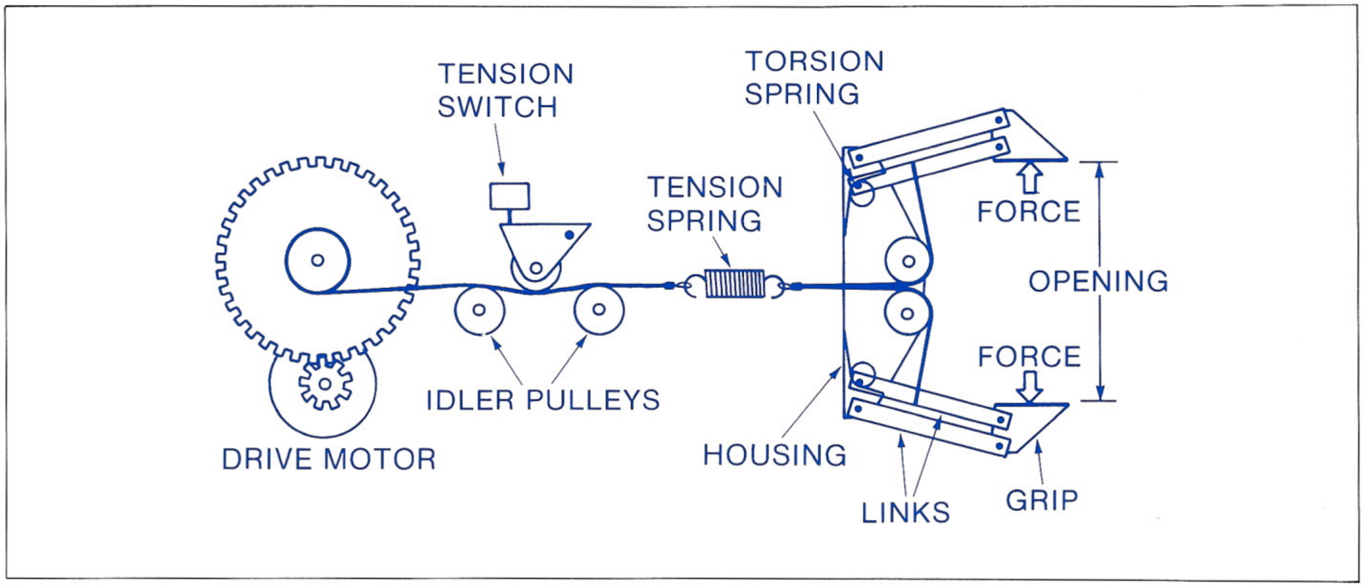


Figure 5. Control system for gripping.

The hand housing is a attached to the output miter gear of the differential gear set. The hand housing supports the two pairs of links, each pair of which terminates in a grip, as shown in Figure 5. The housing, links and grips are attached to each other by small pins. Torsion springs provide the return force to open the hand as the hand cable is slackened. As the hand cable is pulled in, the hand closes upon an object to be grasped and the cable tension mounts, activating a tension sensitive switch. This state of this switch can be read by the control computer which may stop the drive motor as soon as it closes, in which case the grasping force is limited to about 2 ounces (0.3N).

Gripping force can be increased by pulling in more cable after the tension switch closure is detected. Additional cable take-up stretches the extension spring which is mounted in series with the hand drive. This additional cable take-up is converted into gripping force at the rate of one pound for every 52 steps. The relationship between gripping force, hand opening, and drive motor rotation is shown in Figure 6. Thus, gripping force, as well as hand opening, can be controlled by the same cable drive. The performance specifications of the Mini Mover 5 are shown in Table 1.

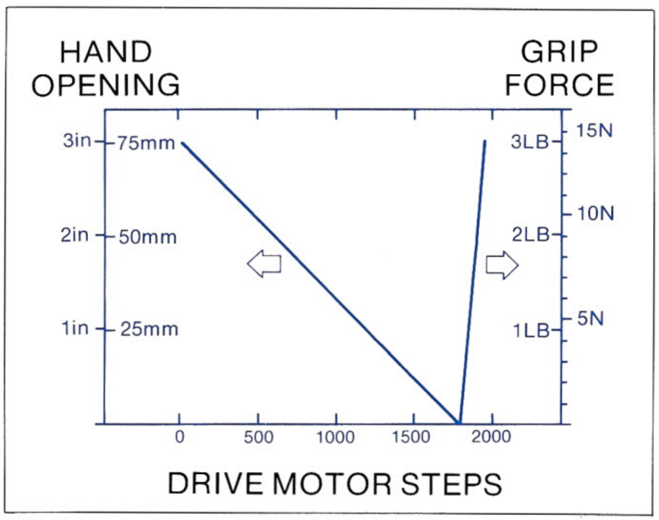


Figure 6. Plot of hand opening and grip force vs number of steps. Grip opening decreases as cable is taken up (left axis), until resistance is encountered. Thereafter, grip force increases (right axis). The plot shows the case when the hand is empty.

Table 1

Mini Mover 5 Performance Characteristics

GENERAL

Configuration	5 revolute axes and integral gripper
Drive	Electric Stepper Motors, open loop
Controller	Microcomputer provided by user
Interface	TRS-80™* or a 8-bit parallel
Program language	ARMBASIC for TRS-80™ (Z-80 driver available)
Power requirement	12 volts, 4 amps DC

PERFORMANCE

Resolution	.013 in (0.3) maximum on all axes
Load Capacity	8 oz (225 gm) at full extension 16 oz (450 gm) at half extension
Gripping force	3 lbs (13 N) max.
Reach	17.5 in (444 mm)
Static load force	4 lbs (18 N) max.

PERFORMANCE DETAILS

Motion	Range	Speed (full load)	Speed (no load)
Base	±90 deg	0.37 rad/s	0.42 rad/s
Shoulder	+144, −35 deg	0.15 rad/s	0.36 rad/s
Elbow	+0, −149 deg	0.23 rad/s	0.82 rad/s
Wrist Roll	±180 deg	1.31 rad/s	2.02 rad/s
Wrist Pitch	±90 deg	1.31 rad/s	2.02 rad/s
Hand	0-3 in (0-75 mm)	3 lb/s (13N/s)	0.80 in/s (20 mm/s)

PHYSICAL CHARACTERISTICS

Arm weight	6 lbs (3 kg)
Interface cable length	3 ft (900 mm)

* Registered Trade Mark of Tandy Corporation

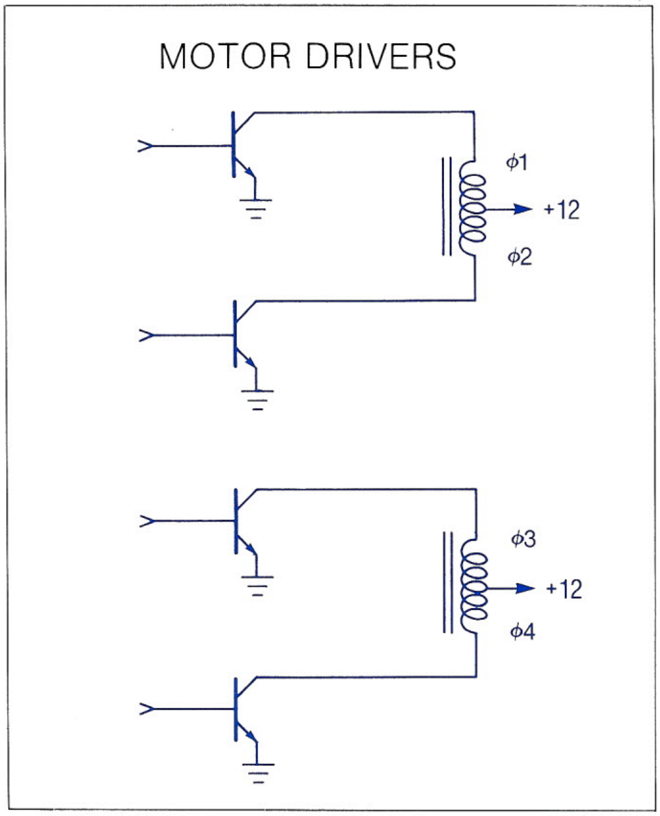


Figure 7. Simplified stepper motor drive circuit. Coils $\phi1$ and $\phi2$ are on one magnetic path. Coils $\phi3$ and $\phi4$ are on another.

Stepping Motor Control

Each of the cable drives is controlled by a stepper motor. The motors used have four separate windings, each driven by a power transistor. The drive is digital, with the transistors switched on or off to obtain a desired pattern of currents in the motor. By appropriately changing the pattern of currents a rotating magnetic field is obtained inside the motor, causing it to rotate in small increments or steps.* In the Mini Mover 5, each of the four coils is individually controlled from the computer. The simplified drive circuit is shown in Figure 7. This allows the pattern of motor currents to be controlled by the computer software, simplifying the drive circuit and reducing its cost.

In order to step a motor, the sequence of binary patterns shown in Figure 8 is output to the desired motor—the pattern on each row of the table, when sent to the corresponding drive transistors of the motor, will cause it to move on step. To step the motor clockwise the patterns are output sequentially from top to bottom. When the end of the table is reached, it is necessary to wrap around to the other end of the table and continue sequentially. To move the motor in the opposite direction, the sequence in which the entries are output must be reversed.

The particular entries shown generate a sequence known as "half-stepping", that is, the angular steps produced by the sequence are half the size specified by the motor manufacturer. Compared to full stepping, half-stepping produces smoother slow speed motions, doubles the accuracy of motor positioning, and reduces the power required. The motors used to drive the Mini Mover 5 are specified by the manufacturer at 48 steps per revolution and thus are stepped at 96 steps per revolution by the algorithm described.

Computer Interface

The Mini Mover 5 interface has been developed to connect the manipulator to Radio Shack's TRS-80™ Level II computer. By changing internal jumpers, the interface can be modified so that it will operate with any 8-bit parallel I/O ports (TTL levels). The interface is organized as seven 4-bit parallel outputs and a single 4-bit input, as shown in Figure 9. Information on the address lines is used to channel the four bits of output data to the appropriate motor drive through individual 4-bit latches. In this way the computer can control the 4-bit phase patterns on each motor with a minimum of hardware. After a phase pattern is sent to a 4-bit latch, it is held by the latch until the next pattern is sent. Outputs of the latches control the power drivers and their respective motor coils, shown previously in Figure 7.

$\phi1$	$\phi2$	$\phi3$	$\phi4$
0	1	0	1
0	1	0	0
0	1	1	0
0	0	1	0
1	0	1	0
1	0	0	0
1	0	0	1
0	0	0	1

CLOCKWISE

COUNTERCLOCKWISE

Figure 8. Table of drive patterns for stepper motor coils.

* More information on the operation and control of stepper motors can be found in References [4] and [5].

The grip switch is connected to one of the inputs of the auxillary port, permitting the computer to close the hand until the gripping force builds up. The other inputs and outputs of the auxillary port are available to the user for experimentation with other sensors or controls. These inputs may be used for tactile, proximity, force and/or position sensors which can be mounted on the hand, arm extremities, and/or the table top. Note also that a four-bit auxillary output port is available as well. This may be used to control another stepping motor such as might be used to drive a work turntable, for example, to control external parts feeders, or synchronize other equipment with arm operations.

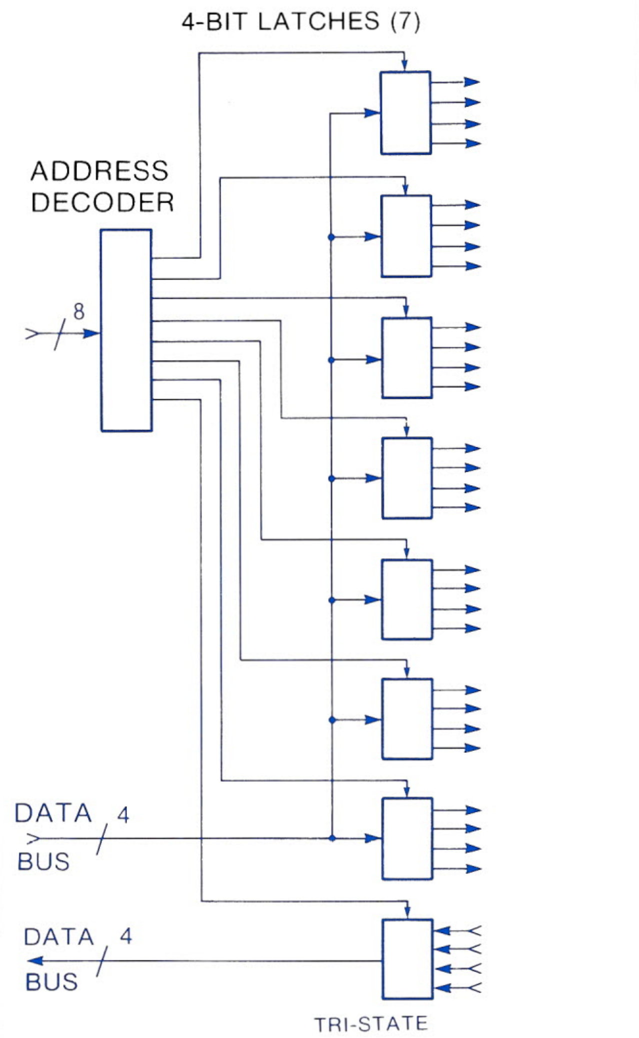


Figure 9. Block diagram of computer interface.

ARMBASIC

A language for control of an arm is important to do useful work with it. For eample, printing on an output device is simplified in BASIC by the PRINT and LIST commands or in FORTRAN by the WRITE command. These high level commands remove the problem of controlling the carriage and printing mechanisms and keeping track of their position to produce the printout. In the same sense, arm control can be more effectively done through such high level commands.

ARMBASIC was developed for controlling the Mini Mover 5 from the TRS-80 computer. ARMBASIC is an extension to the Level II BASIC supplied by Radio Shack, consisting of 5 commands which allow complete control of the manipulaltor. These commands are @STEP, @CLOSE, @SET, @RESET, and @READ. Each of the ARMBASIC commands is implemented in Z-80 assembly language, both to conserve memory and to provide more rapid response of the manipulator. The listings of these routines and more detailed explanations of what the assembly language code does are provided in the Applications Manual [3].

The @STEP command causes each of the 6 stepper motors to move simultaneously. The syntax of this command is:

@STEP (D), (J1), (J2), (J3), (J4), (J5), (J6)

where (D) is an expression for the delay between motor steps, and (J1) through (J6) are expressions for the number of steps each of the six motors is to be moved.

The delay expression (D), evaluated to an integer, determines the speed of the motion. The smaller the delay, the faster the resulting motion will be. For a delay value of zero, the system will wait 1.2 milliseconds between steps. For each additional unit of delay, the driver will wait an additional .03 milliseconds between pulses. This can be expressed as

$$\text{Delay} = 1.2 + 0.03D \text{ (milliseconds)}$$

The joint expressions, (J1), (J2), ... (J6), evaluated to integers, determine the motion of each joint. After evaluation, the sign of each expression indicates the direction each motor should be driven and the magnitude indicates the number of steps.

Additionally, the @STEP command compensates automatically for the interaction of the elbow joint and the hand opening, such that a command to move the elbow joint will not effect the hand opening. Note that the steps specified for joints 4 and 5 refer to the motors driving the left and right differential gears, so that the relation between the

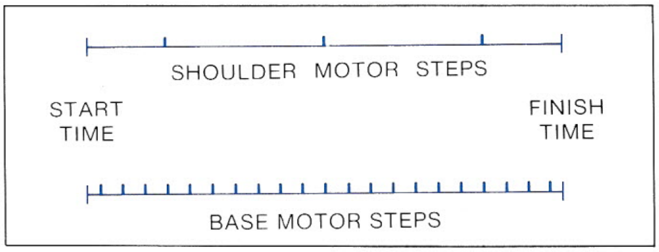


Figure 10. Step timing diagram coordinated movement.

gear positions and the wrist roll and pitch angles must be determined by the user's program.

An important function performed by the @STEP command is to linearly coordinate unequal motor commands. For example, if the base motor is told to move 21 steps, and the shoulder motor is told to move 3 steps, appropriate delays will be inserted between the steps of the shoulder motor so that each joint will begin and end its movement simultaneously, resulting in the smooth and uniform timing shown in Figure 10.

The @CLOSE command causes the hand to close until the grip-switch closes, indicating that the gripping force has built up to the threshold determined by the tension switch. The syntax of the CLOSE command is:

@CLOSE (D)

where the optional delay, (D), determines the speed of closing, as discussed in the @SET command.

The @STEP command puts the manipulator into "manual" mode, so that, by pressing various keys on the TRS-80 keyboard, each joint of the manipulator can be individually moved. The syntax of the SET command is:

@SET (D)

The optional delay (D) determines the speed of motion as discussed in the @STEP command. The keys and the joints that they control are shown in Figure 11. This mode is terminated by depressing the "0" (zero) key. Note that since the driver is capable of reading all the keys held down at once, depressing more than one key will result in all simultaneous movement of the respective joints. Releasing the keys will stop the motion.

As the above commands are executed, the number of steps commanded for each joint are counted and maintained a set of six position registers. This permits the programmer to keep track of the commanded position of the arm under both manual and program control. The @RESET and @READ commands provide access to these registers. The syntax of the @RESET command is simply:

@RESET

This command zeros the contents of the internal position registers and the current of all six drive motors. Turning off the motors in this way allows the manipulator to be

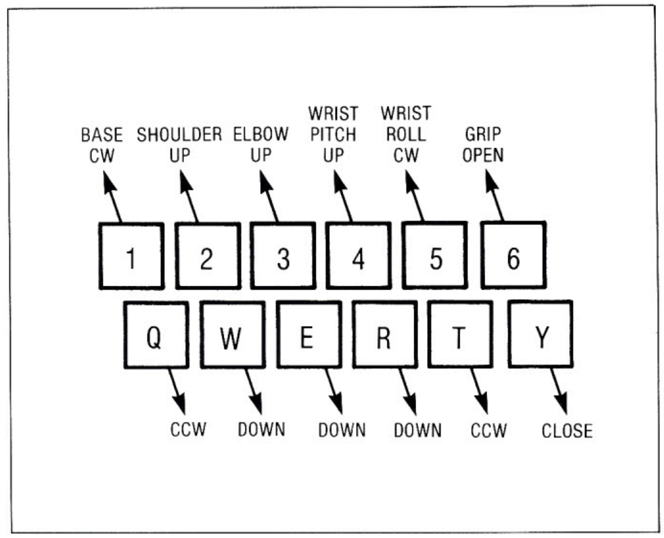


Figure 11. Use of keyboard to control arm.

backdriven (manually moved about). @RESET is used for arm initialization, as discussed in the following section. The syntax of the @READ command is:

@READ (V1), (V2), (V3), (V4), (V5), (V6)

where V1 to V6 are any BASIC variables. This command reads the six position registers into these variables. Thus, the current position of the manipulator is available to the user's BASIC program at any time.

Programming the Mini Mover 5

To illustrate the use of ARMBASIC in manipulation, we will discuss serveral methods of programming a "pick-and-place" task. The task consists of repeatedly picking objects up at one place and setting them down in another. This task is common in industry where parts from a feeder are deposited in another machine or onto a moving conveyor, for instance. To simplify the example, we will assume an unending supply of parts at the pick-up point and continual removal of parts at the destination point.

The task is defined in Figure 12. Pickup is from A and placement is at D. The approach and departure trajectories, AB and CD are usually required for practical reasons: an object resting on a flat surface normally must be lifted before it is translated instead of just sliding it along the surface. In an industrial environment, such a movement could possibly damage the part, the manipulator, or some other object in the workspace.

A simple sequence of ARMBASIC commands for performing the pick-and-place task is shown in Table 2. Movements are performed by the @STEP command, including opening the gripper (statement 60), P=(P1, P2, P3, P4, P5), Q=(Q1, Q2, Q3, Q4, Q5) and R=(R1, R2, R3, R4, R5) define vectors whose elements are the number of steps of each joint needed to move the arm from A to B, B to C, and C to D respectively. S is the number specifying

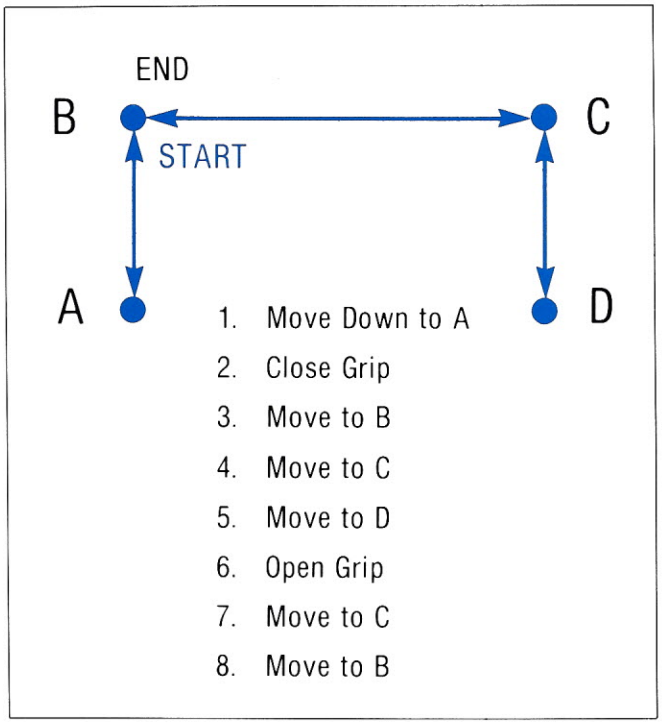


Figure 12. Description of the Pick-and-Place task (side view).

the speed and GR is the number of steps the gripper is to be opened to release the part.

This simple approach is not very practical, as it requires that the number of steps on each joint be known in advance. One practical approach for small tasks is entering the data manually by moving the arm to each of the four positions (A, B, C and D of Figure 12) and letting the computer count and remember the number of steps each joint moves. This operation is frequently called "teach mode."

The teach program shown in Table 3 illustrates this principal. Operating interactively with the computer, the operator manually positions the arm to each of the four positions to specify the pick-and-place task. Each position is obtained by moving the arm, joint-by-joint, using the keys in the upper left hand corner of the keyboard as previously described under the @SET command. Even the desired grip opening is conveyed by teach control. Only the speed is entered numerically.

After the arm is positioned at each of the four locations, the values of the software position counters are read by the @READ command and stored in the vectors A, B, C and D. The elements of these vectors, A=(A1, A2, A3, A4, A5), B=(B1, B2, B3, B4, B5), C=(C1, C2, C3, C4, C5), and D=(D1, D2, D3, D4, D5), are the values of the position counters of each joint. The P, Q and R vectors of the simple program (Table 3) can therefore be obtained by subtraction as follows: P=B–A, Q=C–B, R=D–C. The desired grip opening, GR, is measured by reading the grip position counter before and after closing the grip using the @CLOSE command. (Statements 170-200 in Table 2).

Where information on pickup or placement originates in

Table 2

Simple ARMBASIC Implementation of Pick-and-Place Program

```
10  @STEP  S,-P1,-P2,-P3,-P4,-P5
20  @CLOSE
30  @STEP  S, P1, P2, P3, P4, P5
40  @STEP  S, Q1, Q2, Q3, Q4, Q5
50  @STEP  S, R1, R2, R3, R4, R5
60  @STEP  S, 0,  0,  0,  0,  0,   GR
70  @STEP  S,-R1,-R2,-R3,-R4,-R5
80  @STEP  S,-Q1,-Q2,-Q3,-Q4,-Q5
90  GOTO  10
```

Table 3

Pick-and-Place Teach Program

```
10 REM          *************************************************
20 REM          *                                               *
30 REM          *                MINI MOVER 5                   *
40 REM          *                                               *
50 REM          *             PICK - AND - PLACE                *
60 REM          *                                               *
70 REM          *           MANUAL TEACH PROGRAM                *
80 REM          *                                               *
90 REM          *************************************************
100 @RESET:  REM        ZERO COUNTERS
110 PRINT "PICK - AND - PLACE ROUTINE"
120 PRINT "     USE MANUAL KEYS TO POSITION ARM"
130 INPUT "SPEED ="; S
140 PRINT "POSITION GRIPPER ON PART, TYPE 0 WHEN DONE"
150 PRINT "     ADJUST GRIP OPENING TO CLEAR PART"
160 @SET
170 @READ A1,A2,A3,A4,A5,C
180 @CLOSE:  REM     CLOSE GRIPPER AND MEASURE PART
190 @READ A1,A2,A3,A4,A5,GO
200 G = GO - GC  :REM    GRIP SIZE OPEN LESS GRIP SIZE CLOSED
210 PRINT "POSITION PART ABOVE PICKUP SITE, TYPE 0 WHEN DONE"
220 @SET
230 @READ B1,B2,B3,B4,B5
240 PRINT "POSITION PART ABOVE PLACEMENT SITE, TYPE 0 WHEN DONE"
250 @SET
260 @READ C1,C2,C3,C4,C5
270 PRINT "POSITION PART AT PLACEMENT SITE, TYPE 0 WHEN DONE"
280 @SET
290 @READ D1,D2,D3,D4,D5
300 REM
310 REM    RELEASE PART AND RETURN TO B
320 REM
330 @STEP S,0,0,0,0,0,G
340 @STEP S, C1-D1, C2-D2, C3-D3, C4-D4, C5-D5
350 @STEP S, B1-C1, B2-C2, B3-C3, B4-C4, B5-C5
360 REM
370 REM    WAIT UNTIL READY
380 REM
390 INPUT "TYPE G TO GO"; R$
400 IF R$ = "G" THEN 410 ELSE 390
410 REM
420 REM    RUN THE PICK - AND - PLACE PROGRAM
430 REM
1000 @STEP S, A1-B1, A2-B2, A3-B3, A4-B4, A5-B5
1010 @CLOSE
1020 @STEP S, B1-A1, B2-A2, B3-A3, B4-A4, B5-A5
1030 @STEP S, C1-B1, C2-B2, C3-B3, C4-B4, C5-B5
1040 @STEP S, D1-C1, D2-C2, D3-C3, D4-C4, D5-C5
1050 @STEP S,0,0,0,0,0,G
1060 @STEP S, C1-D1, C2-D2, C3-D3, C4-D4, C5-D5
1070 @STEP S, B1-C1, B2-C2, B3-C3, B4-C4, B5-C5
1080 GOTO 1000
1090 END
```

Table 4

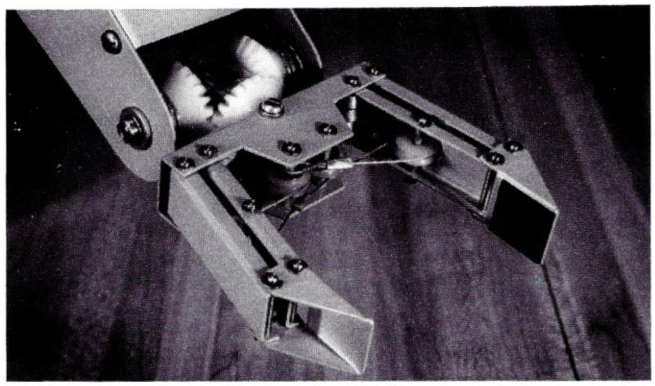
Pick-and-Place X Y Z Control Program

```
10 REM        ************************************************
20 REM        *                                              *
30 REM        *                 MINI MOVER 5                 *
40 REM        *                                              *
50 REM        *         CARTESIAN COORDINATE CONTROL         *
60 REM        *                                              *
70 REM        *                   PROGRAM                    *
80 REM        *                                              *
90 REM        ************************************************
100 REM    DEFINE ARM CONSTANTS
101  H=8.1    :REM   SHOULDER HEIGHT ABOVE TABLE
102  L=7.0    :REM   SHOULDER TO ELBOW AND ELBOW TO WRIST LENGTH
103  LL=3.5   :REM  WRIST TO FINGERTIP LENGTH
104 REM
110 REM       DEFINE OTHER CONSTANTS
111  PI=3.14159
112  C=180/PI       :REM   DEGREES IN 1.00 RADIAN
113  R1=1           :REM   FLAG FOR WORLD COORDINATES
114 REM
120 REM       DEFINE ARM SCALE FACTORS
121  S1=937.8:   S2=S1   :REM  STEPS/RADIAN, JOINTS 1 & 2
122  S3=551.4            :REM  STEPS/RADIAN, JOINT 3
123  S4=203.7:   S5=S4   :REM  STEPS/RADIAN, JOINTS 4 & 5
124  S6=618              :REM  STEPS/INCH, HAND
125 REM
130 REM        INITIALIZATION
131 DIM UU(7,50)         :REM ROOM FOR 50 MOVES
132 U=0
133 @RESET
134 REM
140 REM              READ IN FIRST DATA LINE FOR INITIALIZATION
141 READ X,Y,Z,P,R,GR,S
150 PRINT "SET ARM TO THE FOLLOWING POSITION & ORIENTATION"
151 PRINT "  USING KEYBOARD, TYPE 0 WHEN FINISHED"
152 PRINT "       X = "; X; "INCHES"
153 PRINT "       Y = "; Y; "INCHES"
154 PRINT "       Z = "; Z; "INCHES"
155 PRINT "  PITCH = "; P; "DEGREES"
156 PRINT "   ROLL = "; R; "DEGREES"
157 PRINT "   HAND = "; GR/S6;  "INCHES"
170 @SET
200 GOSUB 5000           :REM GET JOINT ANGLES FOR INITIALIZATION
210 REM  W  IS WHERE WE ARE AT
220 W1=INT(S1*T1)
230 W2=INT(S2*T2)
240 W3=INT(S3*T3)
250 W4=INT(S4*T4)
260 W5=INT(S5*T5)
270 REM
300 REM READ IN NEXT POINT
308 READ X,Y,Z,P,R,GR,S
309 IF X < -100 GOTO 1000
310 PRINT "MOVE TO X,Y,Z,P,R,GR,S"
311 PRINT X,Y,Z,P,R,GR,S
320 GOSUB 5000           :REM GET JOINT ANGLES FOR NEXT POINT
325 REM        C IS THE CHANGE (IN COUNTS)
330 C1=INT(S1*T1)-W1
340 C2=INT(S2*T2)-W2
350 C3=INT(S3*T3)-W3
360 C4=INT(S4*T4)-W4
370 C5=INT(S5*T5)-W5
400 REM    UPDATE WHERE WE WILL BE
410 W1=W1+C1:W2=W2+C2:W3=W3+C3:W4=W4+C4:W5=W5+C5
420 @STEP S,C1,-C2,C3,-C4,C5
425 U=U+1
430 UU(1,U)=C1
431 UU(2,U)=-C2
432 UU(3,U)=C3
433 UU(4,U)=-C4
434 UU(5,U)=C5
450 UU(6,U)=GR
455 UU(7,U)=S
460 IF GR <0 GOTO 500
461 REM   OPEN GRIP IF GR>0
470 @STEP S,0,0,0,0,0,GR
480 GOTO 300
490 REM   CLOSE GRIP AND SQUEEZE IF GR < 0
500 @CLOSE
520 @STEP 100,0,0,0,0,0,GR
530 GOTO 300
540 REM
1000 PRINT " RUN THE PROGRAM"
1010 FOR I=2 TO U
1020 @STEP UU(7,I),UU(1,I),UU(2,I),UU(3,I),UU(4,I),UU(5,I)
1030 IF UU(6,I)<0 GOTO 1060
1040 @STEP UU(7,I),0,0,0,0,0,UU(6,I)
1050 GOTO 1100
1060 @CLOSE
1080 @STEP 100,0,0,0,0,0,UU(6,I)
1100 NEXT I
1110 GOTO 1010
2000 END
2010 REM
5000 REM      SUBROUTINE TO CALCULATE JOINT COORDINATES
5010 REM            ENTER WITH X,Y,Z,PITCH,ROLL, AND R1
5015 REM            RETURN WITH JOINT ANGLES T1 TO T5
5020 P=P/C:R=R/C                                (IN RADIANS)
5030 RR=SQR(X*X+Y*Y)
5040 IF RR<2.25 THEN 6000
5050 IF X=0 THEN T1=SGN(Y)*PI/2 ELSE T1=ATN(Y/X)
5060 IF X<0 GOTO 6000
5070 T4=P+R+R1*T1
5080 T5=P-R-R1*T1
5090 IF T4<-270/C OR T4>270/C GOTO 6000
5100 IF T5<-270/C OR T5>270/C GOTO 6000
5110 R0=RR-LL*COS(P)
5120 Z0=Z-LL*SIN(P)-H
5130 IF R0<2.25 GOTO 6000
5140 IF R0=0 THEN G=SGN(Z0)*PI/2 ELSE G=ATN(Z0/R0)
5150 A=R0*R0 + Z0*Z0
5160 A=4*L*L/A-1
5170 IF A<0 GOTO 6000
5180 A=ATN(SQR(A))
5190 T2=A+G
5200 T3=G-A
5210 IF T2>144/C OR T2<-127/C GOTO 6000
5220 IF (T2-T3)<0 OR (T2-T3)>149/C GOTO 6000
5230 RETURN
6000 PRINT "********** OUT OF REACH **********"
6010 END
6020 REM
9000 REM   COORDINATE DATA FOR PICK-AND-PLACE TASK
9010 REM        STATEMENT 10000 IS INITIALIZATION POINT
9020 REM        STATEMENT 10010-10070 DEFINE TRAJECTORY
9030 REM        STATEMENT 10080 SIGNALS NO MORE DATA
10000 DATA      5,  0,    0,  -90,   0,    0,   50
10010 DATA      8,  0,  1.5,  -90,   0,    0;   50
10020 DATA      8,  0,  0.5,  -90,   0,  -30,   50
10030 DATA      8,  0,  1.5,  -90,   0,    0,  100
10040 DATA      6,  5,  1.5,  -90,  90,    0,   50
10050 DATA      6,  5,  0.5,  -90,  90,  300,   50
10060 DATA      6,  5,  1.5,  -90,  90,    0,   50
10070 DATA      8,  0,  1.5,  -90,   0,    0,   50
10080 DATA   -999,  0,    0,    0,   0,    0,    0
```

a computer, teach programming is often not practical. For example, to move pieces on a chess- or checkerboard would require manually teaching the 64 board locations and the 64 corresponding lift-off points! In this case a coordinate system defining the workspace (or "world") would be more practical. In many situations Cartesian world coordinates are the most convenient. Placing a sheet of graph paper on the worktable facilitates reading of the pick-up and set-down coordinates directly.

The Cartesian coordinate control program shown in Table 4 shows how this is done with the Mini Mover 5 in ARMBASIC. For this program, the locations of the four positions of the pick-and-place task (A, B, C, D) are defined by their Cartesian coordinates (see Figure 1). The *x, y, z,* coordinates (in inches) and pitch and roll angles (in degrees) at the fingertips are:

A=(8, 0, 0.5, -90, 0)
B=(8, 0, 1.5, -90, 0)
C=(6, 5, 1.5, -90, 90)
D=(6, 5, 0.5, -90, 90)



Note that the object is gripped at a point 0.5 inches above the table top (z=0) and is raised (or lowered) 1.0 inches for lift off (set down). Its x location is changed from 8 to 6 inches and its y location changed from 0 to 5 inches. The angular orientation of the gripper is always straight down (pitch=–90 degrees), but the object is rotated 90 degrees on its vertical axis between pickup and set down (roll changes from 0 to 90 degrees).

Data for the Cartesian coordinate program is located after statement 10000. Each data statement specifies an arm position and orientation in terms of x, y, z, pitch and roll, and also includes a sixth parameter, governing the grip opening (if positive) or squeezing force (if negative) after each move, and a seventh parameter governing the speed setting during each move. The actual arm solution, beginning at statement 5000, takes an arm configuration specified by the variables X, Y, Z, P, and R, and finds the joint angles (in radians) that would place the arm in that configuration. It also includes several tests to determine if the postion and orientation requested is within the reach of the arm.

The first data statement gives the initialization point, which is used by the initialization phase of the program, statements 140-260, to tell the computer where the arm is in the coordinate system. Note that the arm position registers are not used by the program (although the @RESET is necessary). Instead, the operator is instructed to position the arm at the initialization point under control of the @SET command. The joint positions corresponding to that point are computed and stored in variables W1-W5. In the main part of the program, the relative offsets from one point to the next are computed and used to step the arm. Thus, all arm movements are made relative to the initialization point.

Since the computer has no way of measuring the arm's joint angles upon startup, such an initialization must be made by every program that relies on an external coordinate system. Similarly, all arm movements are made "open loop," or without position feedback. Therefore, a re-initialization is necessary if the arm is unable to successfully perform a movement due to overloading of collision. The use of open loop control by stepper motors eliminates the need for joint position sensors and associated interface circuitry and is thus an important design tradeoff that reduces the cost of the arm while still providing accurate positioning.

During the second phase of the program, statements 300-530, the arm is moved from data point to data point as the solutions are carried out. An arm solution takes less than one second. The joint angles corresponding to each data point are stored in array UU. After all the solutions are obtained, control is transferred to the third phase, beginning at statement 1000, where the pick-and-place cycle is run repeatedly without coordinate conversions by using the joint angles in UU.

Those who analyze the Cartesian coordinate program carefully will note that it is in fact general purpose, capable of generating arbitrary motion trajectories with up to 50 movements. This is sufficient for many assembly tasks such as building structures from blocks. The power of the ARMBASIC approach can be seen by comparing the simplicity of this program, which is less than 100 lines of code, with previous approaches which have required 8K or more of assembly language coding to do the same type of task. More information on this and other manipulation programs, as well as coordinate transformations, is given in the Mini Mover 5 Reference Manual [3].

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Advances in SWITCHED-MODE Power Conversion

Part II

In our Winter 1979 issue we presented a new concept in the design of switched-mode power conversion circuitry, which, because of its extreme simplicity, flexibility, and efficiency, will without doubt replace most of the conventional electrical power processing methods currently in use. The demand for compactness and efficiency is especially significant in robot applications, where economy in size, weight, and energy is critical.

In Part II, Profs. Ćuk and Middlebrook, the inventors of the new converter topology, continue their fascinating exposition, presenting extensions to the basic design to provide DC isolation, multiple-output power sources, and a physical realization of the sought-for hypothetical dc-to-dc *transformer, a device which converts from* pure dc *(no voltage of current ripple) at one terminal to pure dc (at a different voltage) at the other terminal. The application of the circuit in a highly efficient amplifier for the servo control of a dc motor or other load will also be presented.*

Introduction

In Part I of this series, we provided a review of the basic types of switched-mode power converters and showed how the effort to solve the characteristic problems of these earlier designs led to the development of a fundamentally new converter configuration. Figure 1 shows a summary of the basic converter types and a physical realization of the new converter in its simplest form. The new converter topology embodies all of the desirable features of previous types while retaining none of their liabilities. Whereas other converters rely upon the inductive coupling of energy between the input and output, the new converter uses a capacitor to transfer stored energy between input and output inductors as shown.

Due to the presence of inductors on both the input and output, the current on either terminal remains continuous, avoiding the electrical noise problems associated with switching either the input or output current and resulting in

increased conversion efficiency. The new converter has the desirable property that its output voltage can be either higher or lower than that of the input supply, as determined by the *duty ratio* of the switching transistor (the fraction, D, of the switching period (T_s) that the transistor is turned on).

Also presented in Part I were several important extensions to the basic converter design. These include adding the capability for bidirectional power flow between input and output, coupling the input and output inductors via a single transformer core, and a high-performance switched-mode power amplifier configuration using parallel converters driving a differentially connected load.

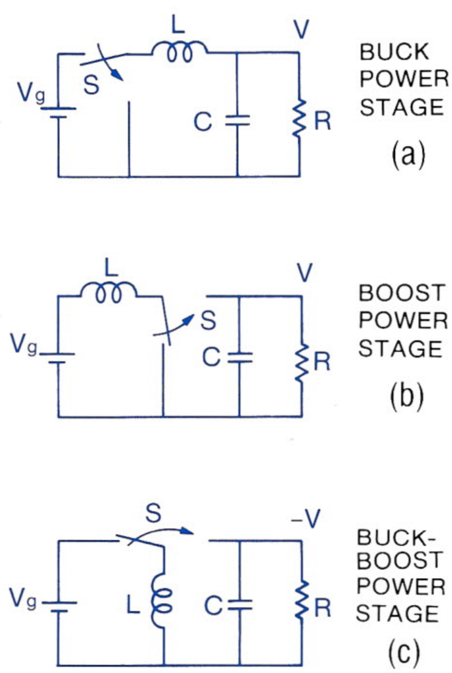
An important result of the coupled-inductor extension of the new converter, apart from the further reduction in the number of components, is that, by proper adjustment of the magnetic coupling between the input and the output inductors, the residual current and ripple at one of the terminals can be reduced *exactly* to zero, resulting in pure dc. Naturally, this motivated the search for a converter configuration which would achieve the desired characteristic of having zero current ripple at *both* input and output *simultaneously*, thus resulting in a physical realization of an ideal dc-to-dc "transformer." (See Figure 8 in Part I.)

In this article, we will show how, by pursuing the desirable property of dc isolation between the input and the output circuits, the sought-for solution for the ideal converter was found, inherently derived from the new converter topology. Since the new topology provides higher performance than all other converter types but may be implemented using fewer components than comparable solutions, it may be said to be an *optimal* design. To illustrate this point, we will present the design of a working circuit that shows the ease of employing the new topology in practical applications.

DC Isolation in the New Switching Converter

All the basic switching dc-to-dc converter types reviewed in Part I, along with the newly introduced converter topology, are distinguished by the elegant method by which conversion is accomplished through the operation of a single switch (double-pole, single-throw) in an otherwise passive energy storage network, as shown in the converters in Figure 1.

Despite this simple structure, which results in the high conversion efficiency characteristic of "switchers," the basic converter configurations all lack one of the properties often required of power supplies: dc isolation between the input and output ports. There is therefore a strong incentive



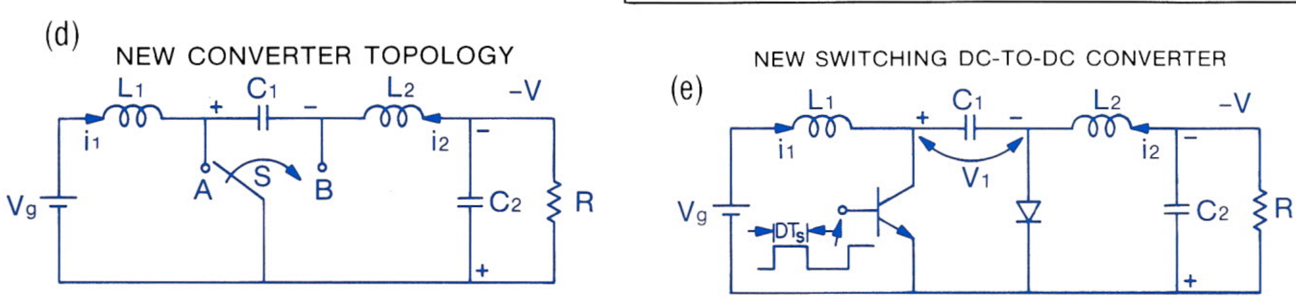


Figure 1. The family of four basic switching converter topologies (a-d) and a practical implementation of the Ćuk converter using a transitor-diode combination (e).

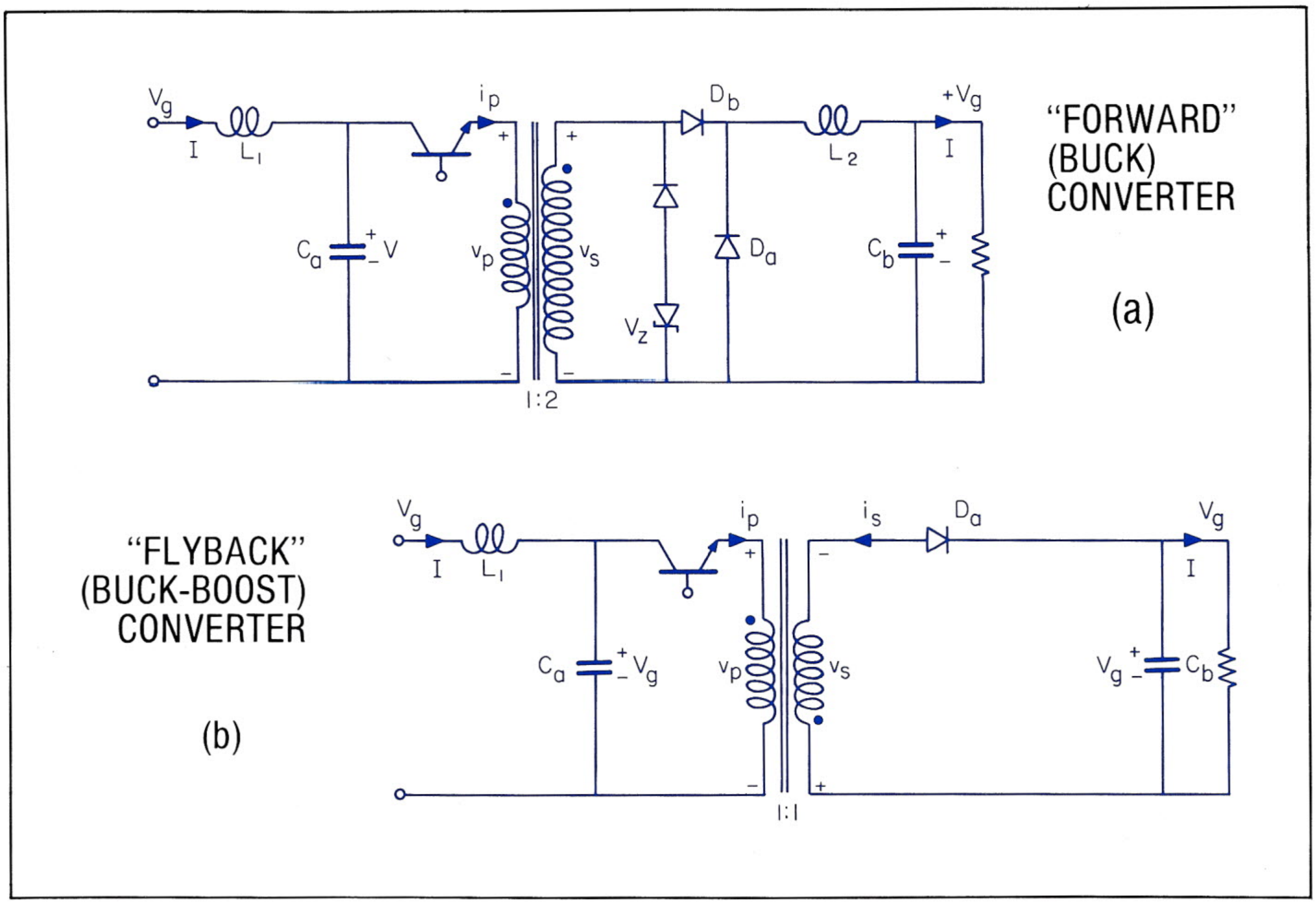


Figure 2. Isolated versions of the basic buck (a) and buck-boost (b) switching converters.

to find a way to introduce an isolation transformer into the new converter design. One could, of course, immediately proceed in a conventional manner and try a "push-pull" configuration using an isolation transformer with a center-tapped primary. However, the consequent doubling of the number of components, along with other practical problems inherent in such a design, favor the search for a less complex single-switch implementation using a "single-ended" isolation transformer.

For example, dc isolation can be introduced into the basic "buck" converter as shown in Figure 2*a*, which is usually known as the "forward converter." Similarly, simple modification of the "buck-boost" converter results in a "flyback" converter (Figure 2*b*) by replacing the original single inductor with a "single-ended" isolation transformer. The resulting configuration also allows the output polarity inversion of the buck-boost type to be reversed as shown, where the transformer terminals of like polarity are indicated by the dots. One is therefore motivated to try a similar approach to modify the new converter topology. The obvious place to insert the isolation transformer is somewhere in the inner loop containing the coupling capacitor, transistor, and diode, in which the actual energy transfer is accomplished. There are three key steps leading to a simple, elegant solution to this problem.

The first step is to separate the coupling capacitance C into two series capacitors C_a and C_b, thus making the original symmetrical switching structure divisible into two halves, as shown in Figure 3*a*, without affecting the operation of the converter. The second step is to recognize that the connection point between these two capacitors, due to its isolation, has an indeterminate dc (average) voltage. This floating potential can then be set at zero by placing an inductance between this point and ground (Fig. 3*b*). If the new inductance is sufficiently large, it diverts a negligible current from that passing through the series capacitors, so that the converter's operation is still unaffected. The final step is merely the separation of the extra inductance into two equal transformer windings, thus providing the desired dc isolation, resulting in the basic isolated version of the new converter shown in Figure 3*c*. [1]

One of the main features of the introduction of the isolating transformer is that it has brought the least disturbance to the original converter operation. In fact, with a 1:1 transformer, the voltages and currents in the input and output circuits are the same as in the original non-isolated version. The only difference is that the original switched current loop now has evolved into two loops with equal currents circulating in the same direction.

It is instructive to consider the current paths, voltage

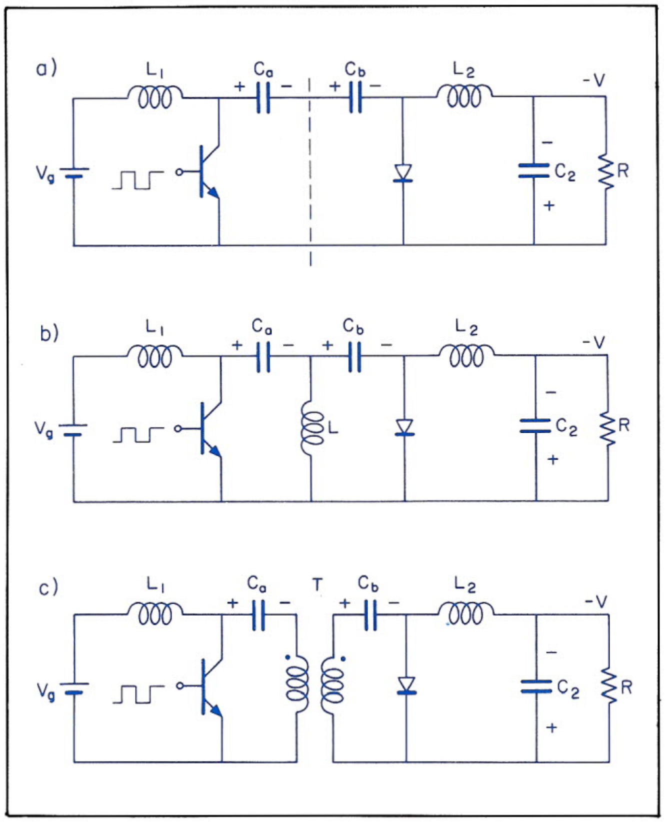


Figure 3. Three key steps leading to the dc-isolated version of the Ćuk converter.

distributions, and energy movements during the two portions of the switching cycle. Figure 4*a* shows the conditions during the interval $D'T_s$ when the switch transistor is off (open circuit). The input current, having previously stored energy in input inductor L_1, must now pass through capacitor C_a and the transformer primary as shown. This transfers energy from L_1 (in the form of current) to C_a (in the form of voltage, or charge). An equal reflected current in the transformer secondary charges C_b through the now conducting diode. During this interval the output inductor L_2 is releasing its stored energy to the load as shown, and the diode thus carries the sum of both the input and output currents.

In Figure 4*b*, the transistor is turned on (closed circuit) during interval DT_s, and the input current is allowed to store energy in L_1. Since C_a (as well as C_b) was charged to a positive voltage (viewed from left to right) during $D'T_s$, it now discharges through the transistor and the transformer primary, transferring the stored energy to the output circuit. Note, however, that when the transistor grounds the positive side of C_a, the voltage drop across the capacitor must (instantaneously) remain the same, so that its right side is pulled down to a negative voltage. This sudden drop is passed by the transformer to the positive (left) side of C_b, and hence to the anode of the diode, cutting it off. Since the output current must now pass through C_b and the transformer secondary, it must match the current through the primary, so that both C_a and C_b discharge their energy into L_2 and the load. One sees that, during this phase of the cycle, it is the transistor that carries the sum of both the input and output currents.

Some of the additional advantages of this new dc-isolated converter become apparent upon reexamining the steps which led to the inclusion of the isolation transformer. Since both windings of the transformer are dc-blocked by C_a and C_b, there can be no dc in either winding. In fact, an automatic volt-second balance is achieved in the steady state, so that there is no problem with "creep" of the transformer core operating point as can occur in push-pull isolation arrangements.

Isolation has thus been achieved in the simplest possible manner by the addition of only the necessary transformer (which is single-ended) and the separation of the original coupling capacitance into

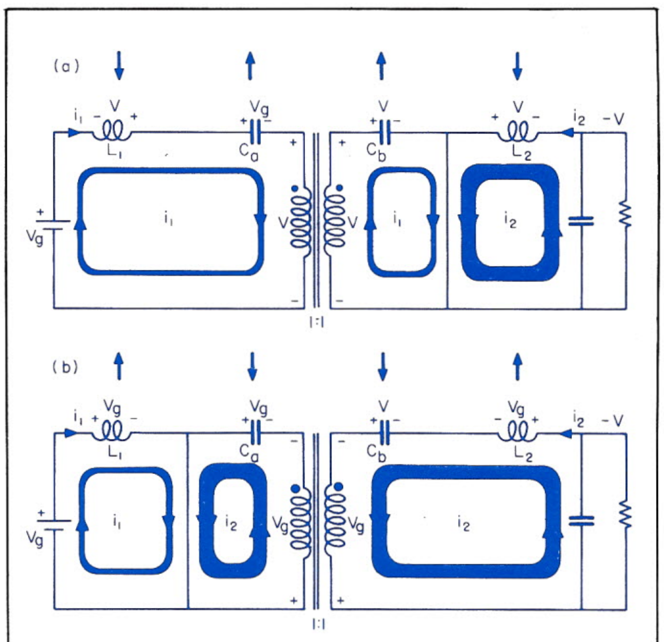


Figure 4. Current and energy distribution in the dc-isolated Ćuk converter: a) interval $D'T_s$ when the transistor switch is open; b) interval DT_s when the switch is closed.

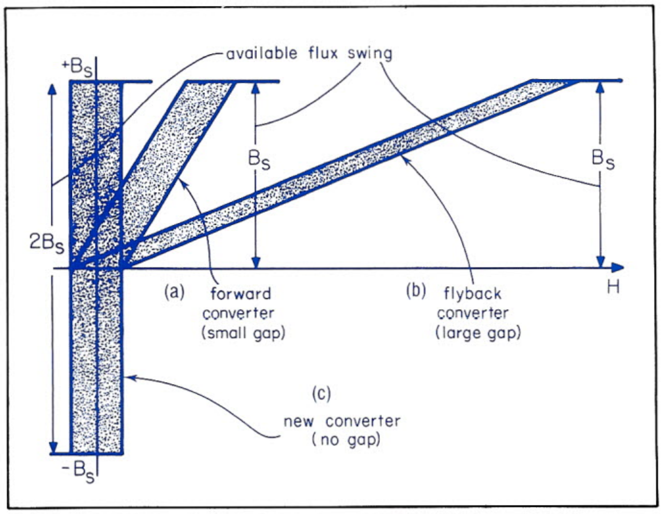


Figure 5. Comparison of the isolation transformer utilization in the Cuk converter and the forward and flyback converters. Twice the flux swing is available in the Cuk converter.

two. Thus, it is apparent that an optimum-topology dc-isolated converter has been obtained which retains all the advantages of the original topology upon which it is based.

Other advantages become apparent upon comparison of the new design with the other popular isolated converters shown in Figure 2. Specifically, for the forward converter the core of the isolation transformer must be gapped, since the magnetizing current is available in only one direction (with an average dc value). The size of the core must be chosen so that the total flux excursion is no greater than the saturation flux B_s of the core material, as shown in Figure 5*a*. [l]

In contrast, in the new converter (Figure 5*c*), magnetizing current in the transformer is available in *both* directions, and so a core that is fully utilized (in terms of flux swing) is only half-utilized in the new converter. Therefore, an ungapped core of half the cross section could be used, with the result that the total flux excursion would be $2B_s$ and the core losses would be correspondingly halved. Similarly, the copper losses would be greatly lowered due to the reduced winding lengths. From the general point of view, these benefits all stem from the fact that in the new converter power is transmitted through the transformer during *both* intervals of the switching cycle, whereas the same average power has to be transmitted during only *one* interval in the forward converter.

Comparison of the transformer properties between the new converter and the flyback converter shows that the disparity is even more extreme, because in the flyback the core gap must be larger than in the forward converter, as illustrated in Fiqure 4*b*. This is because the transformer is really an inductor, and the energy transferred through the converter is stored in the magnetic field (principally in the air gap) during one part of the cycle and released during the other. Consequently, the magnetizing current, which is again available in only one direction, constitutes the total primary or secondary current instead of just a small fraction of it.

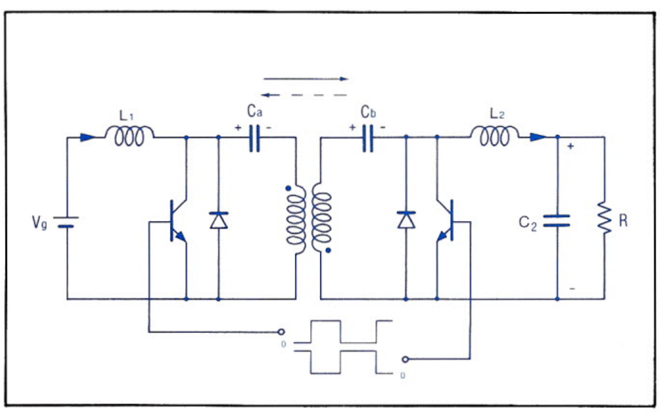


Figure 6. DC-isolated non-inverting bidirectional current Ćuk switching converter, using all npn bipolar transistors. Compare this with Figure 9 in Part I.

The Multiple-Output Extension

Once an isolation transformer has been introduced into the new converter, several other extensions become obvious. There is no reason why the transformer should be limited to a 1:1 turns ratio, and therefore a turns ratio factor N_s/N_p is available for either step-up or step-down in addition to gain control obtained by varying the duty ratio D. Thus,

$$\frac{V}{V_g} = \frac{N_s}{N_p} \cdot \frac{D}{1-D}$$

Also, as in the case of the isolated buck-boost converter in Figure 2*b*, an output voltage of the same polarity as the input voltage may be easily obtained by reversing the polarity of the isolation transformer secondary and changing the direction of the diode and polarity of the coupling capacitor on the secondary side accordingly, as shown in Figure 6. It is interesting to note that this polarity-preserving configuration leads to an implementation of the bidirectional current (two-quadrant) version of the dc-isolated converter using *all npn bipolar transistors*, requiring only positive switch drive signals. (Compare this with the complementary pair, *npn* and *pnp* transistor, version of the bidirectional converter presented in Part I.)

The same holds for the power MOSFET implementation in which only *n*-channel devices are needed. This is of significant practical importance, since *npn* transistors and *n*-channel MOSFETs come in all current and voltage ranges, while *pnp* and *p*-channel devices are very limited, usually to lower current, voltage, and power ratings.

Multiple outputs of different voltages and polarities are easily obtained from multiple secondary windings, or from a tapped secondary winding as shown in Figure 7. All of the benefits of the basic new converter topology are retained in the multiple-output versions; in particular, all the output currents and the input current are nonpulsating. When

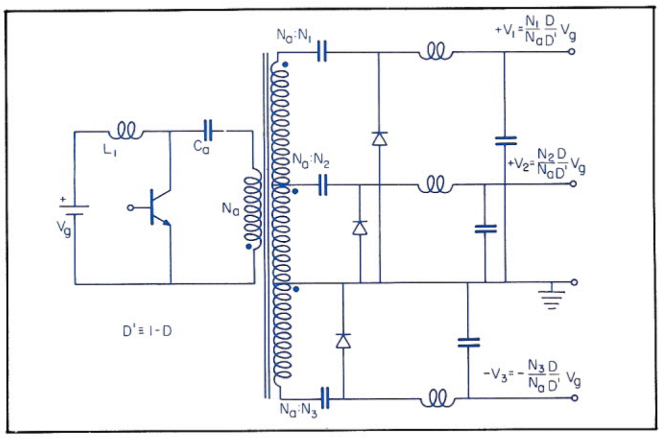


Figure 7. Extension of the dc-isolated Ćuk converter to multiple outputs with arbitrary ratios and polarities.

compared to the conventional approach of designing an isolated, multiple output power supply using a tapped 60Hz transformer followed by several linear regulators, the high performance and cost effectiveness of the new method is obvious. The lower the operating frequency, the more massive a transformer must be. Instead of a bulky 60Hz transformer, a much smaller transformer designed to operate at the switching frequency (20kHz, for example) is used. Instead of the wasteful power dissipation of linear regulation, requiring heatsinks, fans, etc., the new converter typically operates at over 90% efficiency. An additional side benefit is that the latter design is also insensitive to the input line frequency (50Hz, 60Hz, 400Hz, etc.), since the input voltage is supplied by rectifying the ac. Thus, by introducing dc-isolation into the new converter, we have substantially increased its range of application.

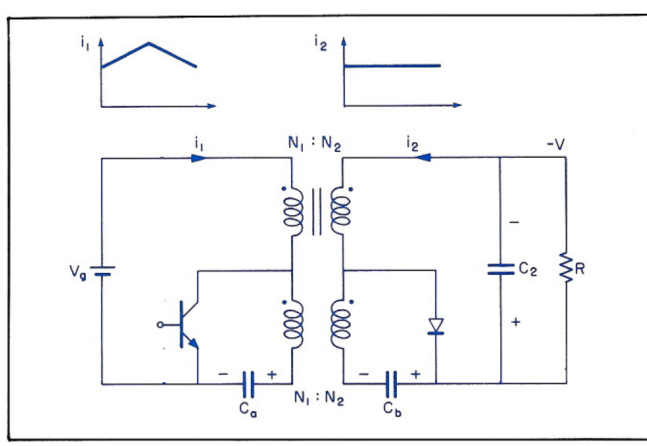
The Coupled-Inductor DC-Isolated Converter

The isolation transformer was imbedded in the basic converter without altering its mode of operation, thus all the modifications and extensions applicable to the basic converter are valid in the isolated case as well. For example, the input and output inductors can be coupled on the same core as shown in Figure 8. As discussed in Part I, zero current ripple may be obtained on either the input or the output through appropriate design of the coupled inductor.

The configuration in Figure 8 may at first seem significantly different from the isolated converter of Figure 3c, apart from the coupling of the inductors. This is because the transfer capacitors C_a and C_b have been relocated to the other side of their respective transformer windings. This change neither alters the converter topology nor affects its conceptual operation. From the practical viewpoint, however, this alteration has important noise reduction advantages. Since the case of an electrolytic capacitor is usually common to its negative terminal, this design effectively grounds the cases of the capacitors, significantly reducing the radiation produced by the switching currents.

While magnetic coupling of the input and output inductors is very desirable for the reduction of ripple, size, and cost, it does introduce an undesirable characteristic, namely the *transient reversal of output polarity* on start-up. Note that in the steady state shown in Figure 8, the average dc currents flow *into* the dots on the coupled inductors, contrary to the behavior of an ordinary ac transformer. During the turn-on transient, however, the ac coupling of the inductors causes the initial current pulse from the input to be reflected in the secondary *in the opposite direction* from the steady-state current, as shown in Figure 9. Although the pulse is of short duration (50 μs. typical), it could result in damage to sensitive loads. The simple addition of an output clamp diode as shown limits the

Figure 8. Coupled-inductor dc-isolated Ćuk converter.



reverse transient to about a volt, or less if a Schottky diode is used.

Just as in the single output case, the same opportunity for coupling exists in the multiple-output isolated converter: any or all of the inductors can be coupled on the same core, as shown in Figure 10. The resulting converter has only two magnetic lumps, one for dc isolation and the other for input and output filtering. Again, by judicious selection of the turns ratios and coupling coefficients, the current ripple may be eliminated on the input or any of the outputs. [1]

These advances notwithstanding, the possibility of zero current ripple on only one side leaves one with a feeling of incompleteness and a desire to accomplish this ideal goal of zero ripple on both input and output ports. That this can indeed be accomplished, with an even further reduction in the size and cost of the circuit, will once again dramatically illustrate the optimality of the new topology.

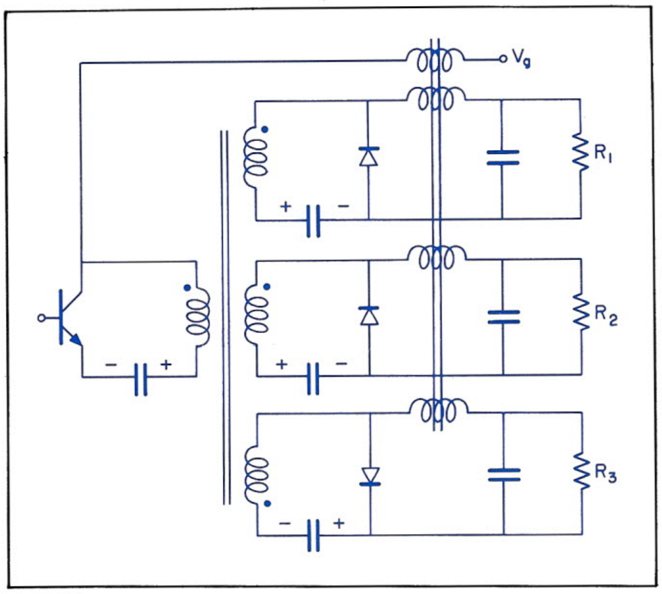


Figure 10. Transformer-isolated Ćuk converter with all inductors coupled on a single core.

The Ideal Zero-Ripple Switching DC-to-DC Converter

In pursuit of the goal just posed, there may be many approaches to follow: for example, two coupled-inductor converters could be cascaded, with one set for zero input ripple and the other for zero output ripple. It is quite obvious that this would be undesirable, for not only would the input power be processed twice, with nearly twice the power losses, but the parts count would be doubled and the original advantages of simplicity and reliability would be lost.

Hence the following objective is posed:

Synthesize a switching dc-to-dc converter which has the least number of components and yet leads to the ideal dc voltage and current waveforms at both input and output simultaneously.

This problem may at first seem formidable and impossible to achieve, but, based on the background material outlined so far, the coupled-inductor concept may be generalized to satisfy our goal. Recall that the original motivation for coupling the inductors was the 1:1 proportionality of the inductor voltage waveforms of the basic converter (Part I, p.9). The key step becomes that of finding a switching topology in which such proportional inductor voltage waveforms are abundant, hence allowing multiple application of the coupled-inductor concept. However, we have already seen such a topology in Figure 3b, where it was

Figure 9. Polarity reversal at start-up in a coupled-inductor Ćuk converter. The output diode provides a safe path for the transient.

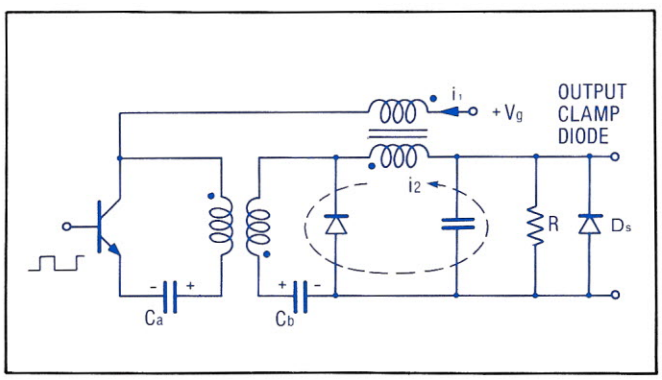
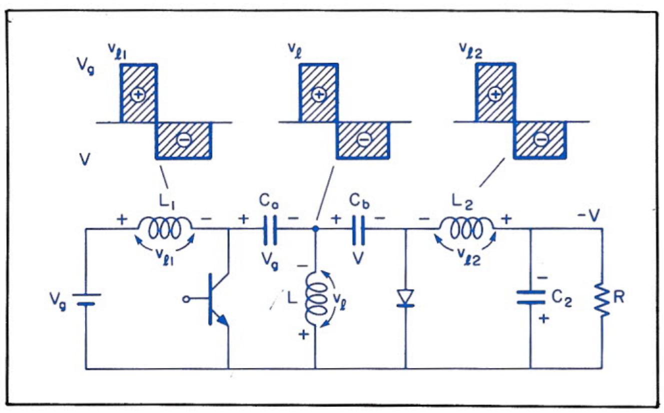


Figure 11. Switching converter with three proportional (1:1) inductor voltage waveforms.



a key intermediate step toward attaining dc isolation. To emphasize the availability of the proportional switching waveforms, this configuration is shown in Figure 11 along with the corresponding inductor voltage waveforms.

It now becomes apparent that the inner inductor L may be coupled with either the input inductor L_1 for zero input current ripple or with L_2 for zero output ripple. However, with a minor modification, *both* current ripples may be simultaneously eliminated. By providing two inductors L_a and L_b in parallel instead of the single L and coupling them as shown in Figure 12*a*, both ripple currents may be transferred inside the converter, resulting in pure dc at each port.

The two inductances L_a and L_b are not coupled magnetically, but are only connected in parallel electrically, hence the configuration has two magnetic lumps as shown in Figure 12*b*, in which gapped "U-cores" are used as one possible implementation. However, these two lumps could be even further reduced by coupling the windings L_a and L_b *magnetically* as well. This is equivalent to magnetically coupling the single inner winding of Figure 11 to both input and output inductors simultaneously, as shown in Figure 13. Note that, as in Figure 12, the input and output inductors L_1 and L_2 are *not* directly coupled, as indicated by the two separate core lines for the input and output sides. However, *unlike* the configuration in Figure 12, the adjustments for zero ripple are no longer independent, due to the magnetic coupling through the common core (L). Changing one air gap alters the ripple characteristics of both sides. Nevertheless, the adjustments are highly convergent and the ideal zero ripple case is readily obtained. [2]

None of the switching topologies shown so far in this section has the important dc-isolation property. However, this feature is now easily obtained by replacing the single winding of the inner leg of the magnetic circuit (L) with separate, isolated windings for the input and output, as shown in Figure 14, with no additional magnetic material required. This step is completely analogous to the one described earlier which led to the original dc-isolated version of the converter (Figure 3*b-c*). However, in the single magnetic circuit of Figure 14, additional benefits are obtained:

The added isolation transformer now has a double role—it not only provides the isolation, but also, through magnetic coupling with the input and output inductors, results in ideal dc current at both input and output simultaneously.

From the magnetic circuit realization in Figure 14*b*, it may seem that a rather special magnetic core configuration is

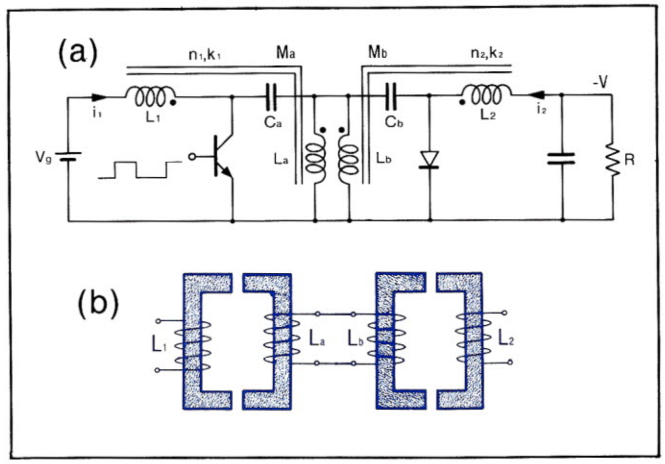


Figure 12. Converter with zero current ripple at both input and output (a) and the realization of the magnetic circuits (b).

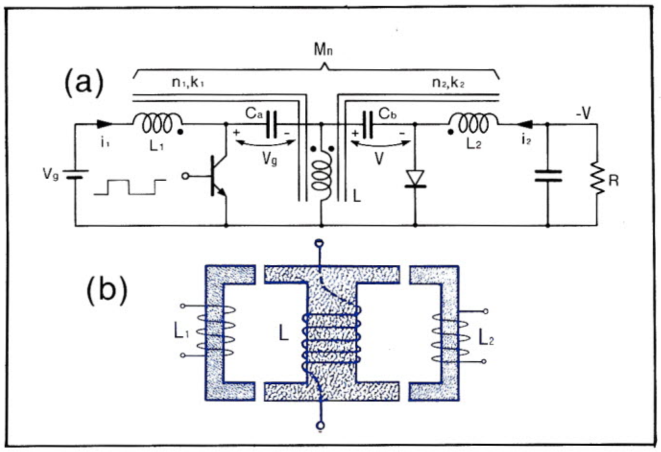


Figure 13. Zero-ripple switching converter with shared inner inductor (a) and one possible core implementation (b).

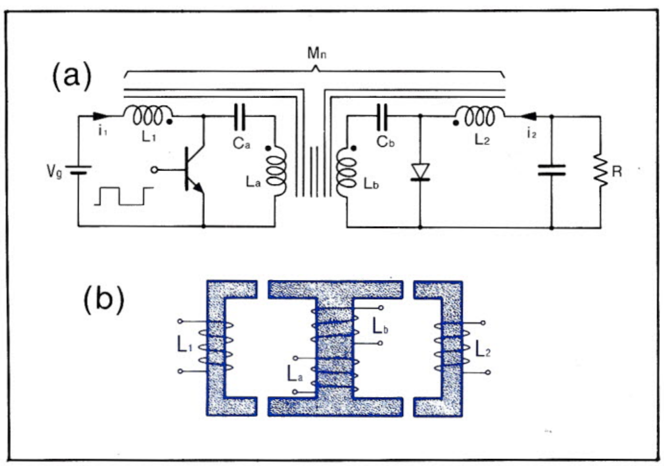


Figure 14. DC-isolated version of the zero-ripple converter obtained by adding a single winding to the magnetic circuit of Figure 13b.

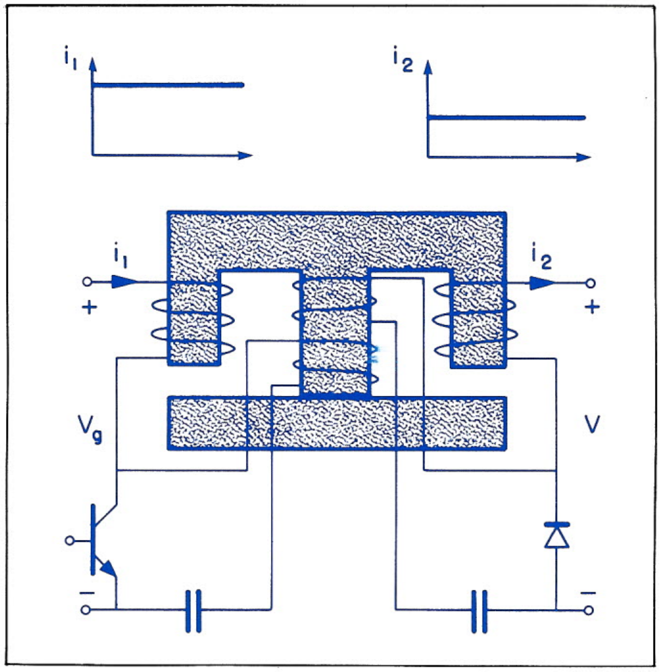


Figure 15. The simplest realization of an ideal dc-to-dc transformer: a four-winding magnetic circuit, a transistor and diode, and two capacitors.

needed, one comprising more than a single core structure. However, the structure illustrated was used only for conceptual reasons to clearly explain each step of the development. A number of widely used standard magnetic cores, such as common E-I cores, for example, can be used for the practical implementation of the switching converter in Figure 14*a* and its single magnetic circuit. In Figure 15 the E-I core implementation of the integrated inductor-transformer differs from standard cores only in that each of its outer legs contains an air gap, as opposed to the usual case in which only the inner leg is gapped. The fact that three bobbins are used (one winding on each leg) is not unusual and is, in fact, common in three-phase transformer designs using E-I cores.

This resemblance in core structure is not a mere coincidence. Merging the three single-phase transformers into a single three-phase transformer results in corresponding savings in core material due to the merging of the magnetic fluxes and the sharing of the common flux paths. Similarly, the core configuration of Figure 15, by merging the two separate inductors L_1 and L_2 and the isolation transformer into this single magnetic structure, results in substantial savings in size, weight, and efficiency.

Thus, a truly optimum dc converter is obtained which has both outstanding features: true dc currents at either port, as well as dc isolation, in the simplest possible topology consisting of a single magnetic circuit, a transistor and diode, and two capacitors. Under the control of a clock signal with variable duty cycle, D, the converter becomes the physical realization of a dc-to-dc "transformer" with an electronically variable "turns-ratio" (Figure 16).

A natural extension of this zero-ripple converter configuration (Figure 15) to multiple outputs is shown in Figure 17*a*. There, a single magnetic circuit M_m with six windings appropriately coupled is capable of providing zero current ripple not only at the input but simultaneously at both outputs as well. The actual physical implementation of its magnetic circuit is a simple three-dimensional extension of the one-output core configuration, as illustrated in Figure 17*b*, providing an additional flux loop common to the central core but separate from the other legs. The three windings of the isolation transformer are placed on the central leg, while the input and two output windings are placed on the three outer legs. Interestingly enough, such a configuration has recently been proposed for a different application, the "Variable Leakage Transformer," in which the third leg is used by a control winding. [3] The extension of this zero-ripple configuration to provide additional outputs (three or more) is performed similarly.

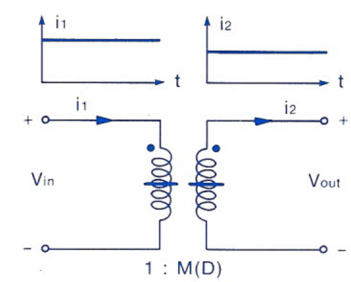


Figure 16. Equivalent circuit symbol devoting the ideal dc-to-dc transformer with constant input and output currents, used as a model of the converter in Figure 15.

The Concept of Integrated Magnetic Circuits

Apart from the usefulness and practical advantages of the various zero-ripple converter configurations previously outlined, their significance extends even further, since their development has led to a new and general integrated magnetic circuit concept.

The coupled-inductor extension of the new converter was the crucial first step in that direction. There, from the conceptual viewpoint, two magnetic components (inductors), which until then had been used only separately to perform their function in circuits, were for the first time *integrated into a single magnetic circuit* (single core) with two windings. While it looked like a classical ac transformer from the structural viewpoint, it indeed performed the function of two separate inductors, when polarity marks

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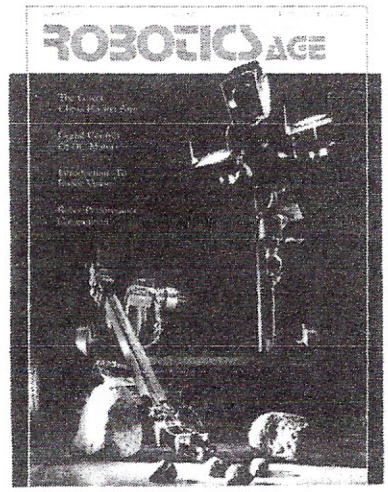

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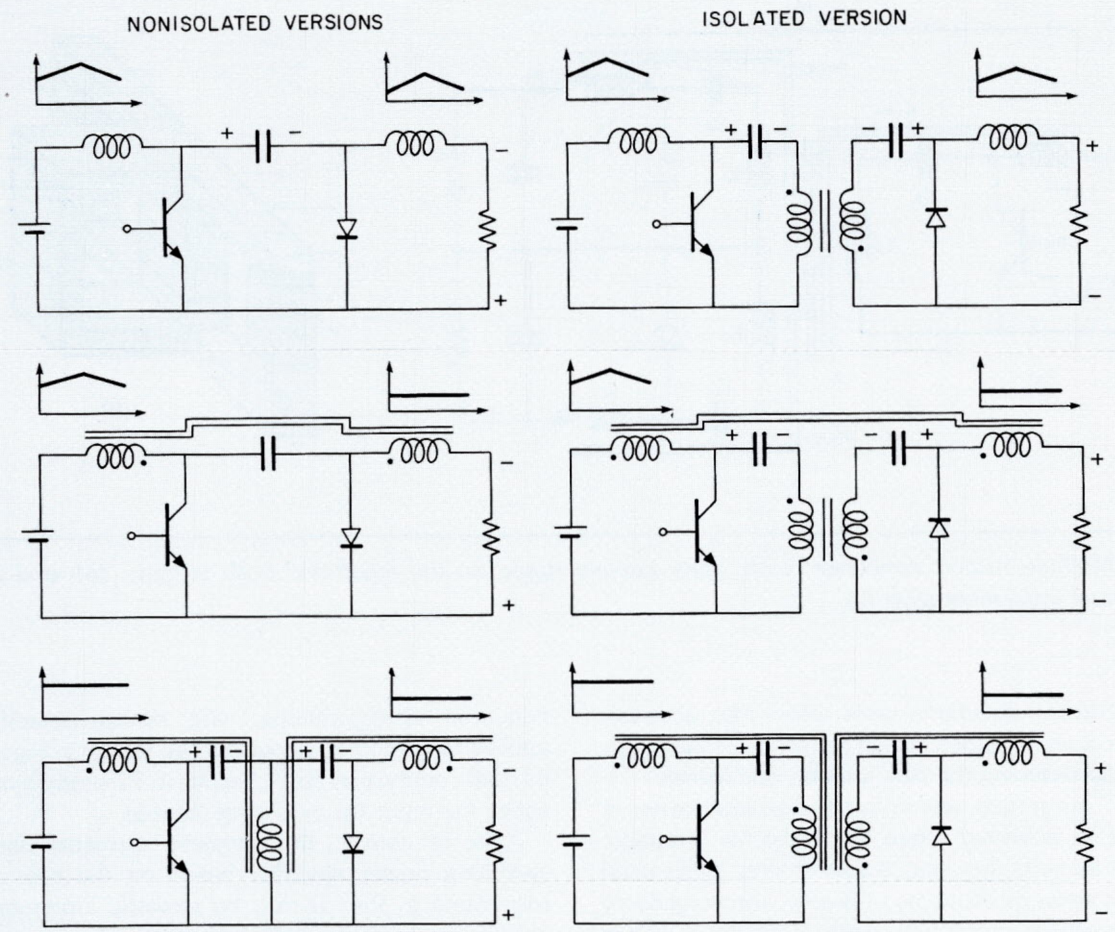
The Evolution of Zero Ripple DC-to-DC Switching Converters



The search for new efficient, low noise switching converter topologies was originally motivated by the desire to reduce or possibly eliminate some of the major problems which limit "switchers," such as the large pulse currents at either the input or the output port or even both. For example, in a conventional buck-boost (flyback) converter, both input- and output-port currents are large pulses, leading to severe conducted and radiated electromagnetic interference (EMI). The basic Cuk converter (nonisolated version) was a substantial step in the direction of reducing this problem by creating nonpulsating input and output currents. However, the unique topology of the Cuk switching converter and in particular the proportional voltage waveforms on their two inductors has led to a powerful new concept: the coupling of inductors. Besides the obvious reduction in complexity, yet another significant advancement has been acomplished: current ripple at either input or output is not only reduced but completely eliminated. The natural outgrowth of this new technique is a switching configuration which employs a single magnetic circuit with three windings and achieves zero current ripple at both ports simultaneously.

For many practical applications, dc isolation between source and load is essential. The next key step in the development is the incorporation of an isolation transformer in an optimum single-ended manner, which leaves the fundamental features of the basic Cuk converter intact. Hence, coupling of the input and output inductors leads again to zero current ripple at either end. Finally, the crowning achievement of the converter development is its final evolution into a topology which truly emulates the desired electronically controllable ideal dc-to-dc transformer. This ultimate switching dc-to-dc converter configuration possesses both outstanding features: true dc currents at both ports and dc isolation in the simplest possible topology, consisting of a single magnetic circuit with four windings, two capacitors and a single switch implemented by the usual transistor-diode combination.

In summary, a long journey in the development of optimum switching converter topologies has been successfully completed: from the conventional buck-boost with large pulsating currents at both input and output ports, through new converters with bolt currents nonpulsating, to an ideal dc-to-dc switching converter, all featuring nonisolated as well as isolated versions. The basic Cuk converter, as well as many of its extensions and applications, are protected by a series of patents. [7-10]

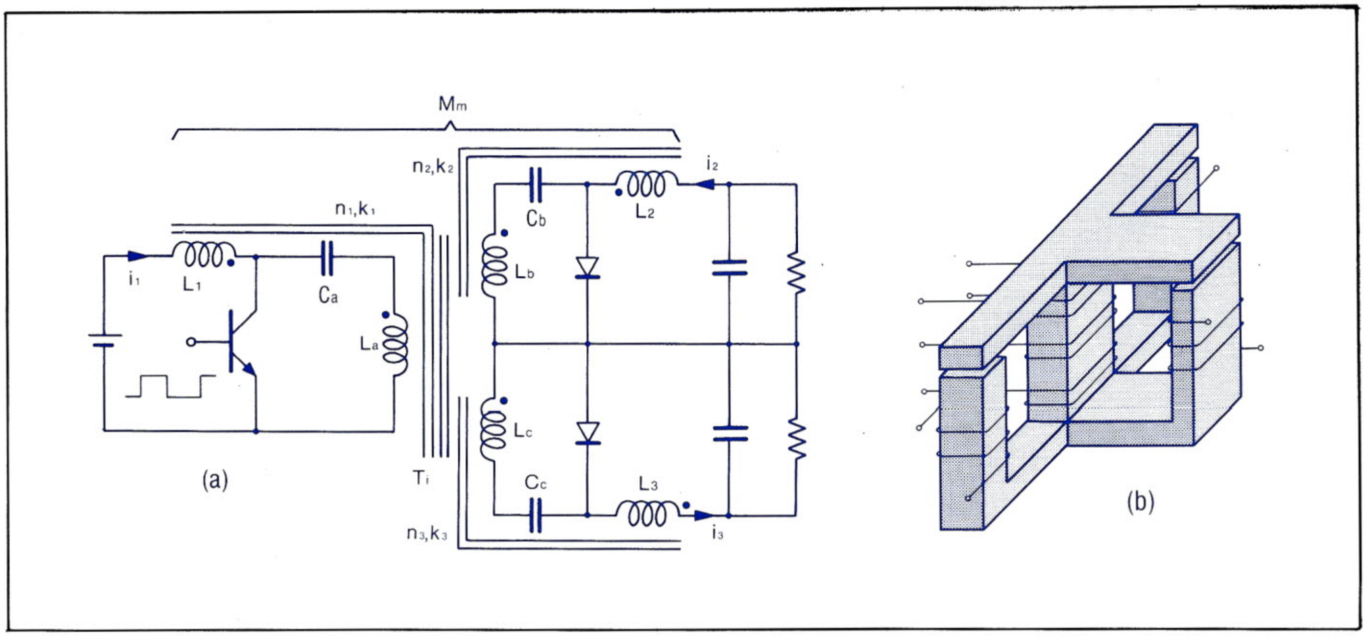


Figure 17. Multiple-output converter with zero current ripple on the input and both outputs (a) and the single magnetic circuit implementation (b).

and actual current directions were taken into account. Furthermore, it even outperformed the separate inductors by significantly reducing the size, weight, and losses.

The natural outgrowth, and in fact the generalization, of this concept is achieved when such diverse magnetic components as inductors and transformers, again used exclusively as separate elements until now, are merged into an integral magnetic circuit with multiple windings. When put into the proper circuit configurations (such as those of Figs. 13-15,17), they not only perform the original functions, but even tremendously improve the performance of the converter (ripple currents reduced to zero), with additional savings in size and weight and increased efficiency.

An analogy with the development from discrete electric circuits to modern integrated electronics can also be drawn. Just as electronic components and their interconnections were integrated on a common silicon medium, with electron current as the binding carrier, we now have diverse magnetic components integrated into a single magnetic circuit, with the core material as the medium and magnetic flux as the binding carrier. Whereas previously we could describe the current distribution in a complex electronic circuit, we now, in the case of switching converters, have a complex magnetic circuit, with a corresponding flux distribution, which is superimposed on and related to its electrical complement. For this process of reducing the separate magnetic components into a single magnetic circuit with accompanying savings in size and weight, and owing to its similarity with the integration of electrical circuits, a generic name *integrated magnetics* is proposed.

This new concept is applicable to a broad spectrum of electrical circuits involving magnetic components. To illustrate this, we will demonstrate its use in different converter configurations, with similar benefits. When applied to the SEPIC converter [4], shown in Figure 18*a*, or its dual counterpart (*b*), it results in zero ripple current on either the input (*a*) or output (*b*) side.

Also, of course, the magnetic elements used in the switching power amplifier based on the new converter (described in Part I) may be similarly integrated. In the configuration shown in Figure 19, the basic amplifier has been modified by employing integrated magnetics to have dc isolation (for use with ac line voltage input, for example) and zero ripple on both the input and the load. The resulting circuit has only two magnetic circuits, each with four windings.

These examples illustrate how, in a complex switching configuration consisting of a number of storage elements (inductors, transformers, and capacitors) and switches, interconnected to perform some useful function, such as dc-to-dc conversion, dc-to-ac inversion, the otherwise separate magnetic components can be merged into an integral magnetic circuit with multiple windings. The prerequisite for such a simplification is the existence of synchronized and proportional voltage waveforms on the inductors and transformers, as in the case of dc-isolated version of the new converter previously described.

Conclusions

A long and most rewarding exploration of switching dc-to-dc converter topologies has come to its fruition in establishing a practical switching configuration which truly emulates the ideal dc-to-dc transformer function. Let us conclude by summarizing some of the major milestones

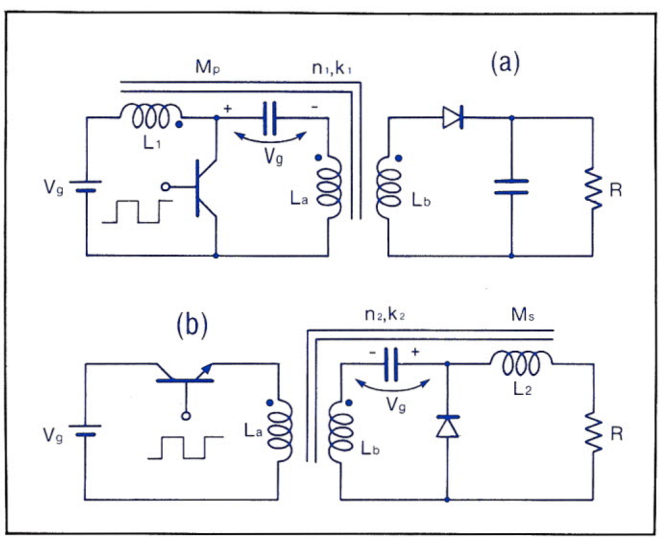
encountered along the way.

The traditional approach taken by many researchers and practicing engineers is indeed very simple: let us first get the required dc-to-dc conversion function by using some simple switching mechanism (such as buck or buck-boost) and then cure its problems (such as pulsating input or output currents and severe EMI) later, such as by adding complex filter and storage elements to "clean up" the signals.

Our approach, however, has been just the opposite: from the very beginning we considered that storage and energy transfer elements, together with the switches, are an intergral part of the problem. Moreover, we have not only attached extreme importance to converter topologies but now have extended the previous topology of *electrical* connections into its complementary topology of *magnetic* connections through the newly introduced *integrated magnetics* approach.

At every point in the development, we introduced additional complexity by adding circuit elements, electrical or magnetic connections for only two reasons: because it was the optimal method of obtaining a desired feature or function—or as an intermediate step towards a further simplification. Even when a seemingly simple configuration was achieved in the basic converter, the desire to still further simplify and improve performance led to the new coupled-inductor concept, which has now been generalized

Figure 18. The integrated magnetic circuit concept, when applied to two converter configurations, the SEPIC converter (a) and its dual counterpart (b), results in zero current ripple at the input (a) or output (b).



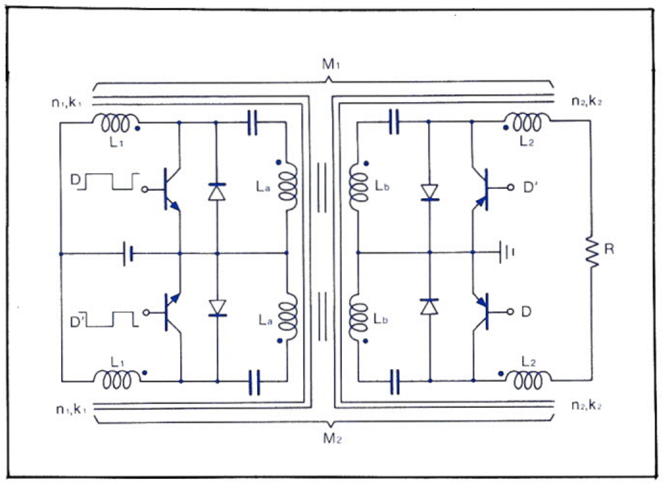


Figure 19. Integrated magnetics applied to the Ćuk switching power amplifier. Compare with Part I, Figure 19.

into the integrated magnetics concept.

As a result of this approach, dc-to-dc conversion topologies have now been extended to include bidirectional power flow (two-quadrant converters) and dc-to-ac inversion and power amplification (four-quadrant converters) as presented in Part I, and now to the dc-isolated and ideal zero-ripple converters presented here. Thus, the approach has been generalized to include the whole spectrum of Power Electronics applications.

Appendix: Circuit Specifications for a Switched-Mode Power Amplifier

In Part I of this article (pp. 14-18) the application of the Ćuk power stage to a new push-pull power amplifier configuration was presented, along with a detailed discussion of its performance. The Ćuk amplifier features broad frequency response (flat over 20Hz-20kHz), low distortion (less than .1% THD), and high efficiency (appx. 90%), using inexpensive, commonly available components. Its capability for bidirectional power flow, as with the other bidirectional configurations described in Part I, make it highly suitable for use in driving loads from which stored energy can be recovered, such as for performing regenerative braking of dc motors.

Interestingly enough, the same amplifier may be used for the servo control of ac induction (Tesla) motors. When an ac signal source at a constant slip frequency relative to the motor's speed is used as input, optimum torque control, as well as the desirable regenerative braking, may be obtained.

We present here the design of a working Ćuk amplifier

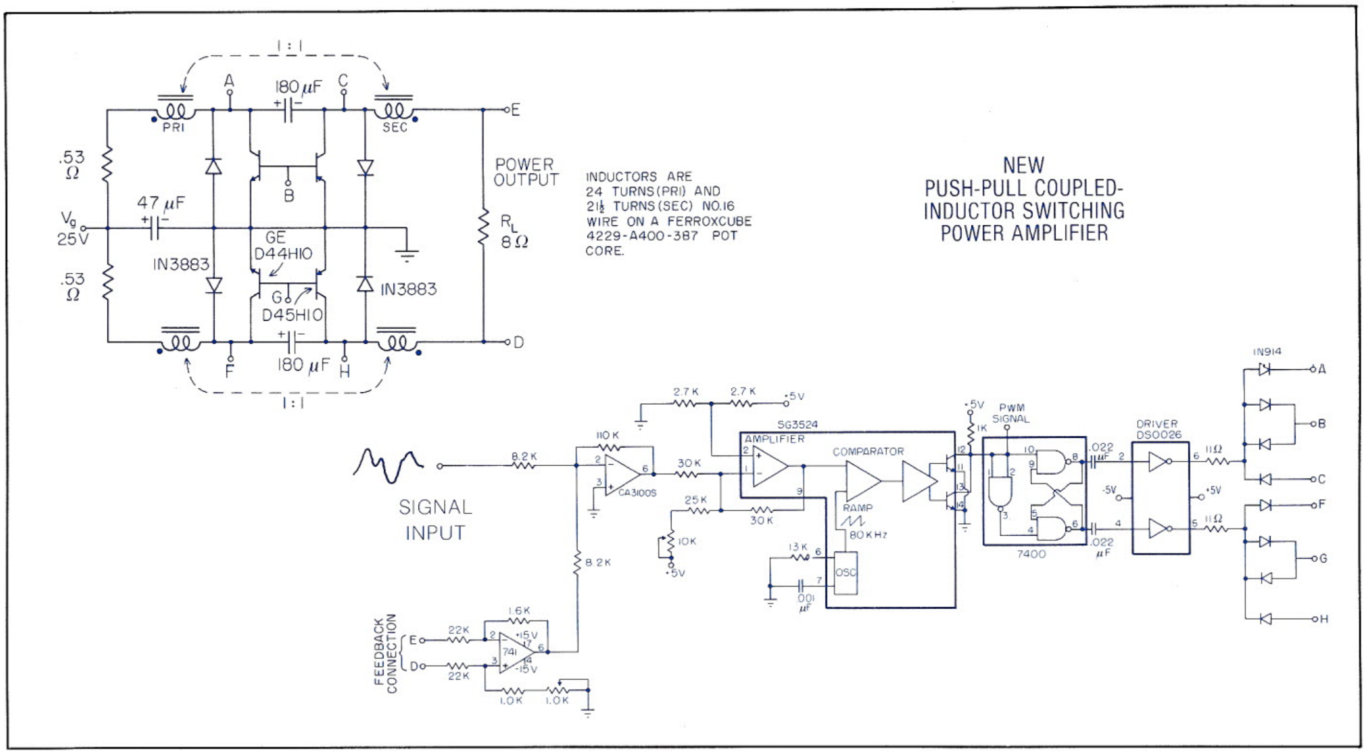


Figure 20. A push-pull switching power amplifier based on the Ćuk coupled-inductor power stage.

suitable for use either as an audio amplifier or a servo driver for small dc motors (up to 40 Watts). The circuit, shown in Figure 20, is based on the coupled-inductor, non-isolated version of the Ćuk converter. [5]. Note that the load is connected differentially across the two power stages, instead of relative to ground. (A photograph of the assembled amplifier was shown at the end of Part I.) Each of the coupled inductors uses a single ferrite "pot" core assembly, wound as specified on the single bobbin, secondary first. Observe the polarity markings on the diagram so that current flowing "into the dot" on each winding will travel in the same direction around the core.

The voltage across the load (E-D) is differentially sensed by the 741 op amp and compared with the input signal using a RCA CA3100S op amp. R_1 is adjusted to obtain the best differential output from the 741. The excellent frequency and phase response of the Ćuk power stage eliminates the need for any frequency compensation of the feedback. A switching regulator integrated circuit SG3524, by Silicon General, is used in the feedback loop to generate a pulse-width-modulated (PWM) signal with an 80kHz switching frequency. R_2 provides DC balance and is adjusted to produce zero output voltage in the absence of an input signal. Logic gates (7400 NAND) connected as a flip-flop produce two out-of-phase input signals for the DS0026 drivers, which produce the ±5V drive signals for the switching transistors. Diodes (1N914) were used in a modification of the "Baker clamp" to improve the transistor switching times, while still retaining the feature of *automatically* preventing the overlap of the transistor on times.

In many dc motor control applications, it is desirable for the servo input voltage to determine the *current* to be supplied to the motor instead of the voltage. Current sensing for use in feedback control can be accomplished by inserting a small (0.1 ohm) sense resistor in series with the load and applying the voltage across it to the feedback inputs E and D, with the gain of the differential amplifier suitably increased.

The 0.53 ohm resistors on the input side of the switching power stage serve to optimize the harmonic distortion characteriestics of the amplifier at a slight expense in operating efficiency. (See Part I.) For applications in which distortion is not a critical factor, these resistors may be omitted.

The use of coupled inductors in the power stage, although eliminating the switching ripple current on the output, imposes a limitation on the maximum available output current, as *both* the input and output currents produce magnetizing flux with the shared core that must be kept below the core's saturation point. Using a non-coupled configuration, Cuk converters capable of up to one kilowatt (over 1HP) output power have been constructed. [6]

Future articles in Robotics Age will report on new developments and present additional Ćuk converter circuit designs, such as a switching servo amplifier with current feedback for torque control of dc motors and a design for the servo control of ac induction (Tesla) motors.

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Patents

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[10] Slobodan Ćuk and R. D. Middlebrook, "DC-to-DC Converter Having Reduced Ripple Without Need for Adjustments," U.S. Patent Application, June 15, 1979.

NEW PRODUCTS

The Thermwood Series Six Robot

The Series Six Industrial robot, manufactured by Thermwood Corporation, is a hydraulically powered, jointed arm design, continuous path robot. It has six independent axes (expandable to nine) and a 180° universal joint type wrist. The machine is specifically designed for spray painting applications but can also be used for welding and material handling.

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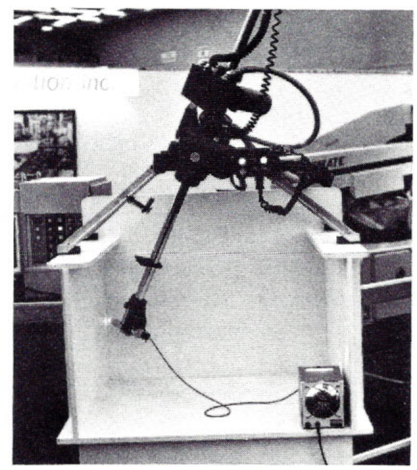
Welding Robot by Unimation



A portable robot that makes difficult vertical and out-of-position welds is being introduced by Unimation Inc.

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Ron Reeve, President of Advanced Robotics Corporation states, "Advanced Robotics Corporation believes the 80's is the era of the robot. How the robot meets the production challenge of the 80's is ultimately dependent on the user . . . management groups need to be adventurous enough to dig in and solve the problems of implementing robot automation in their own shops. For those who are willing, there are manufacturers available who will take the time and effort to work closely with them, helping to build the bridge of the 1980's and bring automation to the American production environment."

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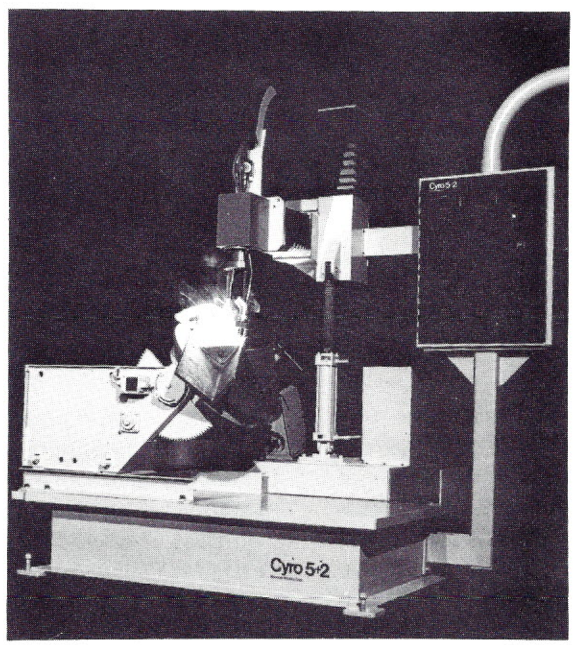

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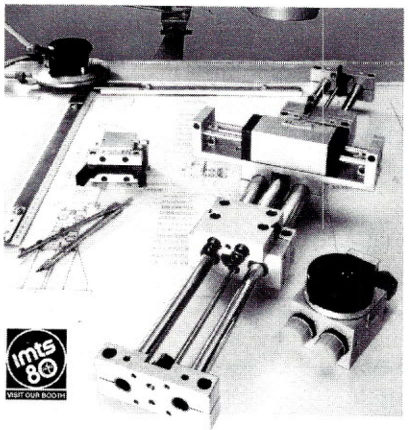


The Fibro/Manca workpiece handling program ia a unique method of assembling custom-designed automation systems. By using standard "off-the-shelf" linear, rotary elements, and grippers, a new "do-it-yourself" capability is now available for American machinery design engineers and users after ten years of industrial application in Europe.

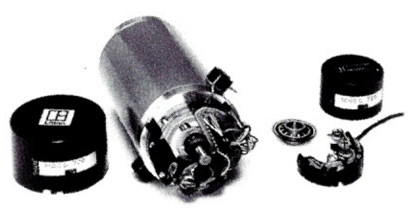
By combining various linear and rotary elements, any desired transfer motion can be obtained. The systems can be as simple or as complex as the needs demand and are not restricted to any set number of fixed axes. Virtually any movement of a human hand or arm can be duplicated by a Fibro/Manca system.

Standard Linear elements range from 1.25″ to 50″, with load capacities ranging from 44 lbs. to 4,000 lbs. Rotation elements provide up to a full 360° motion, with comparable load capability. Workpiece grippers are available in more than 50 different models, and specially designed jaws can also be factory-built. Programmable electronic or hard-wired controllers permit a wide variety of application. Target repeatability of within .0004″ can be obtained, with travel speeds up to 40″/sec. Contact Manca, Inc., Leitz Building, Rockleigh, NJ 07647. (201) 767-1100.

Circle 7

Low-Cost Modular Encoders

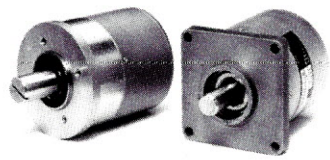
Litton Encoder Division's line of low-cost, kit-type, modular optical encoders consist of a hub-disk assembly, photohead assembly and cover designed for mounting on a motor or shaft assembly. The units feature gallium arsenide LED sources, phototransistor sensors, optical-quality glass commutator disks with chromium deposition pattern, and direct DTL, TTL, CMOS and component compatibility. They are available with voltage options of +5V, +12V, +15V and +24V. Sizes range from 1.50″ diameter (Model 715 shown above unmounted) to 2.10″ diameter (Model 720 shown mounted). Mounting hub I.D. may be tailored to customer requirements.



Designed for mounting on a motor or shaft assembly, these modular models provide a convenient and inexpensive means of sensing rotary speed or angular position in applications where space is at a premium and little inertia and no additional torque can be added to the system. Contact: Marlene Votion, Litton Encoder Division, 20745 Nordhoff St., Chatsworth, CA 91311, (213) 341-6161.

Circle 8

Heavy Duty Encoders



The encoder division of Litton Systems Inc. has announced a new heavy duty version of its standard Model 76 absolute shaft position encoder. Heavy Duty Model 76 has been developed specifically to withstand tough industrial environments, including humiditiy, machine oil, dust and dirt. It has a large shaft and rugged bearings that can withstand shaft loading up to 76 pounds. Like the standard Model 76 it uses highly reliable gallium arsenide light sources and carries Litton's five-year guarantee against field failure.

The heavy duty model is supplied in gray code, natural binary or 8421 binary coded decimal and offers a choice of 10 resolutions with DTL and TTL compatible outputs. The rugged frame is available in two mounting configurations. The compact encoder is 3 inches by 2.65 inches in diameter.

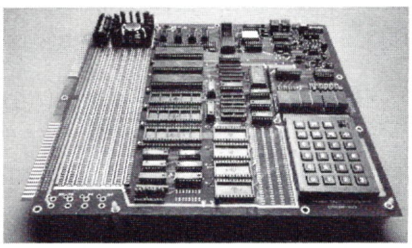
Typical applications include material handling systems, industrial robots, process control systems, computing scales and antennas. Several versions of Heavy Duty Model 76 are now available off the shelf. Send inquiries to Marlene Votion, Litton Encoder Division, 20745 Nordhoff St., Chatsworth, CA 91311. (213) 341-6161.

Circle 9

The SUPERKIM Single Board Computer

The SUPERKIM SBC is based on

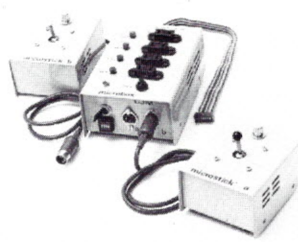
the popular 6502 microprocessor and features more advanced interfacing and real-time control capabilities than other 6502-based SBC's. Prewired sockets are provided for up to four 6522 interfaces (one 6522 is provided). Each 6522 provides two 8-bit bidirectional ports, four output/interrupt input lines, one bidirectional 8-bit shift register interface, and two programmable interval timers. Two onboard 6530's provide additional timers, ROM, and I/O. Additional sockets are provided for up to 4k bytes of 2114 RAM (1K supplied) and up to 16K EPROM (2732) or 8K (2716). Other features of the unit are: an RS232/TTY serial interface; 8 vectored, priority, latched interrupts; cassette interface; onboard power supply (less AC transformer); and a 3x10 inch prototype area. 200 gold-plated wire-wrap pins are provided for easy connection to the bus and all I/O lines.



The SUPERKIM is suitable for use as a microprocessor control system and a complete real-time multitasking system, with up to four separate real-time clocks and sophisticated interrupt handling. SUPERKIM is availabale for $395 from Microproducts, 2107 Artesia Boulevard, Redondo Beach, CA 90278. (213) 374-1673. Circle 10

Joysticks and AC Control for Apple

CJM Industries Inc.. is marketing two new products for the Apple computer—the Microbox and Microstik. The Microbox plugs into the Apple game socket and has four AC outlets that can control external devices by simple commands from keyboard or programs. Four LEDs provide visual status of each port or socket. Loads are switched by solid-state components that isolate and protect the Apple.



Two heavy duty jones plugs and sockets connect matching joy-stick modules called Microstiks. Three pushbuttons provide additional external inputs to the computer.

A tutorial manual and demonstration cassette are included, describing various applications including household appliance control, motor and speed control, relay and solenoid switching, and enhancing games and graphics input. Future modules will include videotape recorder control for computer interactive instruction, audio tape control for CAI, and solenoid and relay add-ons for simple experiments in robotics.

The Microset, comprising the Microbox and two Microstiks, sells for $164.95. The components may also be purchased separately. CJM Industries Inc., Dept. MB, 316B Victory Dr., Herndon Industrial Park, Herndon, VA 22070. (703) 471-4291.

Circle 11

Spectrum Analyzers for Microcomputers

In addition to the real-time audio spectrum analyzer that Eventide introduced for the Commodore PET computer, a similar unit has been introduced for the TRS-80 and Apple computers. The VTU02, for the TRS-80, and the AIB232, for the Apple, divide the audio spectrum from 20 hertz to 20 kHz into 31 one-third octave bands and displays them with their relative amplitudes on the computer CRT.

The units can be used for measuring sound and noise levels, optimizing the equalizaiton of a hi-fi or public address system, checking the frequency response of audio components and recognizing speech and sound patterns, (useful in voice and control systems). The VTU02 plugs into the TRS-80 expansion port—and provides an equivalent port for further expansion—and the AIB232 has an interface board that fits one of the Apple interface slots. The AIB232 can make dynamic use of color, as the color of each bar of the display is under software control; one or several bars can change color in real time.

Great flexibility in the manipulation of the analyzed data is possible because of the capabilities of the computers. Channel data can be stored and compared with past, future and other information. Programs to access the analyzer are written in BASIC. Three are provided with each unit: interactive operation, minimal operation and self-test.

The VYU02 sells for $595, and the AIB232 is $545. For details, write Eventide Clockworks Inc., 265 W. 54th St., New York, NY 10019 or call (212) 581-9290.

Circle 12

Hobby Robot Equipment

Hobby Robotics Co. has been formed to develop, manufacture and market a line of robotic modules designed specifically for the growing hobby market.

HR intends to provide the basic building blocks to allow the hobbyist to custom-build his own robot devices and systems.

The company is currently developing interfaces that will allow HR modules to be controlled by many of the more popular computers.

Now on the market is the RBU-II Robotic Mobile Base Unit, a lightweight, durable mobile platform 18 inches wide by 24 inches long. The unit is driven by twin three-inch tracks powered by two 6 to 12 volt gear reducers. Its carrying capacity is 100 pounds at a speed of 2 feet per second, drawing an average of 4 amps.

RBU-II is configured to support the SU-II Structural Unit and other modules now in development and sells for $495 plus $15 shipping and handling in the United States. Delivery is within 60 days of receipt of certified check or money order.

The SU-II Structural Unit is the first add-on module for the RBU-II. The module provides multiple platforms for mounting and housing hobbyist-supplied utility equipment—batteries, motor controllers, air pumps and receivers, valves, sensors, manipulators and microcomputer controllers. Price: $49.95 plus $5 shipping and handling.

A free catalog describing the units is available from Hobby Robotics Co., P. O. Box 997, Lilburn, GA 30247. (404) 923-1656.

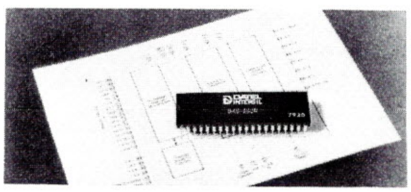
Circle 13

Low Cost 16 Channel 8-Bit DAS

The DAS-952R is a single-chip, 16 channel, 8 bit data acquisition system costing only $37.50 in quantities of 1-24. This system allows any one

of 16 single-ended channels of analog information to be selected and digitized to 8 binary bits of resolution at a system throughput rate of up to 17.5 KHz. The system is designed to interface easily with microprocessors, allowing a wide range of control application.

Monolithic CMOS technology allows this system to be fabricated on a single chip and contained in a compact 40 pin plastic DIP, requiring only an external reference, clock, and connection to power supply (+5V @ 1 mA max.). The input multiplexer allows direct access to any of 16 single-ended analog input and provides necessary logic to permit additional channel expansion.



Connection of the multiplexer output to the A/D converter input is by external pin connection, thus permitting easy input signal conditioning such as sensor linearization or use of a sample-hold. A 256R network ensures monotonicity while a chopper-stabilized comparator makes the converter highly resistant to thermal effects and long term drift.

Full scale range for the DAS-952R is determined by the voltage of the external reference source, which may be selected to yield a full scale range from .512V to 5.25V, thereby allowing selection of LSB size (resolution) from 2 mV to 20.5 mV. Latched and decoded channel address inputs, latched three-state TTL data outputs and microprocessor-compatible control logic permit easy interfacing to microprocessors.

Delivery is stock from Datel-Intersil, 11 Cabot Boulevard, Mansfield, MA 02048. (617) 339-9341.

Circle 14

Voice I/O for the Sorcerer

Cognivox, a unique new accessory for your Exidy Sorcerer™ computer, opens up a whole new area of man-machine interaction. For the first time speech recognition and voice response are combined in a single low-cost voice I/O terminal.

The Cognivox system includes both the hardware and an extensive software collection. The hardware comes complete with microphone and audio amplifier/speaker enclosure, ready to plug in the I/O port of your Sorcerer. The unit recognizes up to 16 words with 98% accuracy and has a 16-word response vocabulary.

The software provided consists of the basic driver programs, two applications program packs (a total of 8 programs), two sophisticated voice operated video games (VOTH and VOICETRAP), plus a Talking Calculator program that converts your Sorcerer into a four-function floating point calculator that talks!

The basic unit is $149, with a 32-word vocabulary unit selling for $179. Similar units are available for the TRS-80™ and for any Z-80 system, from Voicetek, P. O. Box 388, Goleta, CA 93017.

Circle 15

RS232 Interface for Turtle

Terrapin Inc. now provides a pluggable interface from any standard RS232 line to its Turtle robots. The new TST-1 interface plugs into any standard 110-volt wall socket, into any standard serial line and

then into the Turtle, making the robot completely pluggable for the TRS-80, Apple, DEC and other computers.

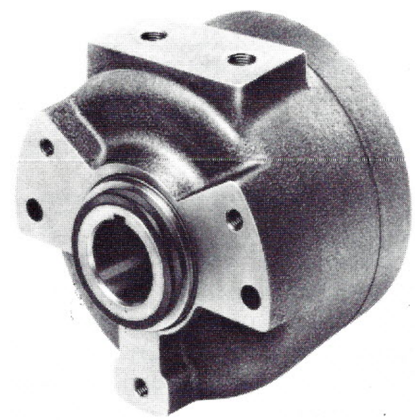
The interface provides the Turtle with the parallel interface it needs, as well as the necessary 18 volts DC of power (at 1.5 amps) that it takes to run one of the small robots. The TST-1 may be used to hook to computers directly or for remote input and output using a modem.

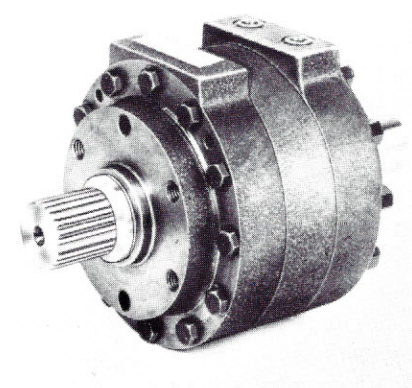
TST-1 interfaces also allow users to hook up more than one Turtle to a computer, terminal or modem. The interfaces are chainable, thanks to their settable escape character, enabling a number of them (set with different escape characters) to be hooked together, each one driving its own Turtle.

The TST-1 is $150, or $125 if purchased with a Turtle, from Terrapin Inc., 678 Massachusetts Ave., Cambridge, MA 02139. (617) 482-1033.

Circle 16

Most Efficient, Compact Power Source From Bird-Johnson





The Bird-Johnson Hyd-Ro-Ac is the simplest, most compact device available for the production of high torque. It is an efficient power source for all types of mechanical motion, including turning (up to 280°), positioning, steering, opening and closing, swinging, and other functions requiring reciprocating rotary power.

It has a broad range of applications, wherever hydraulic systems are utilized in manufacturing, particularly in industrial robots. Its highly adaptable, direct coupling solid-shaft and hollow-shaft models permit clean system designs that often eliminate expensive and cumbersome linkages.

The working parts of the Hyd-Ro-Ac are internally sealed, so that the wear and contamination problems of plunger action, part of the mechanics of most other types of hydraulic actuators, are bypassed, resulting in very low maintenance requirements. Rotary actuators offer distinct torque advantages for start/stop operation and the acceleration of large masses. Wherever reciprocating rotary power is used for indexing, bending, lowering, shifting, mixing, metering, driving, lifting, clamping, and any other number of mechanical functions, design engineers will find the Hyd-Ro-Ac ideal. Contact Mr. Scott Golding, Sales Representative, Bird-Johnson Company, Fluid Power Division, 110 Norfolk Street, Walpole, MA 02081. (617) 668-9610.

Circle 17

SME Publications Catalog

The Society of Manufacturing Engineers has announced the availability of its 1980 publications catalog, free on request.

The 44-page listing describes handbooks, textbooks, reference books, home study courses, conference proceedings and technical papers available from SME.

In addition to printed materials, the catalog lists videotapes, cassette audio tapes and films produced by SME on a wide range of manufacturing subjects. Technical papers available on microfiche are also listed.

For a copy of the catalog, write or call the Society of Manufacturing Engineers, Marketing Department, 1 SME Drive, P. O. Box 930, Dearborn, MI 48128. (313) 271-1500, Ext. 353.

Circle 18

Consulting Firm Provides Robotics-Related Services

Logistics Technology International, Ltd. provides services in studies and analyses, research, and consulting along with training and education. The capabilities of LTI include applications of advanced technology to diverse areas of engineering, management, and social science, including aerospace and defense studies, computer software development, military/business logistics support, automated manufacturing design, and environmental impact analyses.

LTI offers particular capabilities in the area of industrial robotics and automated systems, including: robot manipulator path control software; distributed processing systems design; man-machine system modeling; extraction of object attributes

from visual input; speech recognition system design; high level computer language for programming robot actions; scheduling robot tasks in automated systems; software design, development, and testing for specialized applications in computer-aided manufacturing systems; sensor feedback utilization; data base management for automated systems; productivity evaluation; logistics support analyses of automated systems; life-cycle costing; and cost-benefit/cost-effectiveness studies.

For further information on services in the above or related categories, contact: Logistics Technology International, Ltd., 2707 Toledo St., Ste. 603, Torrance, CA 90503. (213) 328-4051.

Circle 19

Software for Home Control

Soft-Sonic, a collection of programs for home control, has been introduced by Blankenship & Associates, Computer Electronics.

For use with the Apple computer and a BSR Ultrasonic System 10-X (Sears Home Controller), the package includes transducer hardware, interface cable and software on diskette. The programs provided permit control of lighting, appliances and other devices in the home through user-defined timed sequences (Applesoft) or by voice command using Heuristics Speech Lab (Integer BASIC).

These BASIC programs—with a compact, relocatable machine language subroutine—provide an inexpensive yet fully reliable system. Orders are shipped postpaid for $39.95. Add $2 for c.o.d. Contact John Blankenship, BACE, P. O. Box 52785, Atlanta, GA.

Circle 20

Eyecom II Handbook

Spatial Data Systems, pioneers in image processing, has just completed printing a new, 40-page handbook entitled "Eyecom II Picture Digitizer and Display."

Within its pages, readers will find a completely illustrated, easy to understand, overview of image processing—from initial scanning of images, through digitizing to ultimate display and all variations of display capability. Included are chapters on black & white displays and enhancement, graphic and alphanumeric overlays and pseudo-color and true color displays. Software programs compatible with the PDP-11and other minicomputers are also dicussed in the new handbook.

Free copies of the handbook along with information on particular image processing problems may be obtained from: Spatial Data Systems, Inc., P. O. Box 249, Goleta, CA 93017. (805) 967-2383.

Circle 21

The Robot Mart

The Robot Mart is a retail and mail order business devoted to supplying parts, kits, materials, books, electronic controllers and software to robotics hobbyists. It is a dealer for the Terrapin Turtle and other robotics kits, including the Technic line of plastic construction materials. Gears, shafts, motors, rechargeable batteries and basic construction materials—plastic and metal sheets and shapes—are included in the Robot Mart catalog, scheduled for distribution in June.

The catalog will cost $3, or $5 overseas, and includes a one year update service. For additional information, write or call the Robot Mart, 19 W. 34th St., New York, NY 10001. (212) 695-5108.

Circle 22

Survey of Industrial Robots

Technical Insights Inc. has recently published "Industrial Robots—Key to Higher Productivity, Lower Costs," a 230-page report written to help managers search through the maze of robot information being generated today.

The fact that many robots are available today poses a serious problem for the industrial manager, according to the publisher. Robots vary in complexity, performance, and, of course, price. Thus the decisions regarding which robot to buy, when to buy it and for what use are difficult ones for the industrial manager. The contents of the report were designed to help with those decisions.

The study includes detailed information about more than one dozen robot makers and their products, an in-depth look at robot technology, a section on various uses of industrial robots, and advice regarding economic and other considerations that the buyer should understand before installing an industrial robot.

A final chapter looks to the future to provide insight into how research in software, vision and touch will effect robots still on the drawing board. An appendix listing 60 of the most significant robotics patents of recent years is also included.

The report is available for $375 from Technical Insights Inc., P.O. Box 1304, Ft. Lee, NJ 07024.

Circle 23

ORGANIZATIONS

Robots V to be held in Dearborn

The Robots V Conference and Exposition will be held October 28-30 in Dearborn, MI, under the sponsorship of the Robot Institute of America, the Society of Manufacturingg Engineers, and the recently formed Robotics International of SME.

General chairman John J. DiPonio said the conference will emphasize the use of industrial robots to increase productivity and new developments in robot technology. DiPonio is a project coordinator with Ford Motor Co.'s North American automotive operations, Dearborn.

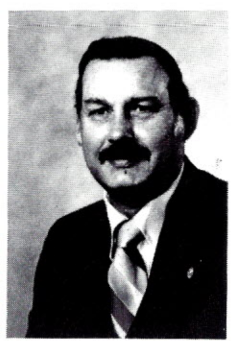
More than 25 technical presentations will be given in six sessions, DiPonio said. The topics: planning the robot installation, justifying robot applications, employee introduction, maintenance and safety, current applications, and research and development.

Application papers will describe new developments in assembly, die casting, finishing and painting, inspection, machining, material handling and welding.

Technology advances in sensing devices and vision systems, new peripheral equipment and set ups, and reducing down time will be described. Other speakers will examine social considerations, including employee acceptance of robots and productivity impacts, DiPonio said.

The exposition will be "the largest concentration of industrial robots in the United States this year," according to DiPonio. Exhibitors will include Arc Systems, ASEA, Astek Engineering, Auto-Place, Cincinnati Milacron, DeVilbiss, Planet Corp., Prab Conveyors robot division, Reis Machines, Robotics Technology, Seiko Instruments, Thermwood, and Unimation Inc. Conference registration fees will be $310 for members and affiliate members of RIA, SME and RI, $360 for non-members. Certificaiton credits will be awarded to conferees. Exposition-only registration will be $2 for member, $3 for others.

Further conference details are available from Patricia Van Doren, Society of Manufacturing Engineers, P. O. Box 930, Dearborn, MI 48128. (313) 271-1500, Ext. 369. For exhibit information, call Cecil Darnell, Ext. 306.



Radeke to Head Robot Division

Michael Radeke has been appointed manager of the industrial robots division of Cincinnati Milacron Inc., succeeding the retiring John A. Fulmer.

Radeke has held technical, marketing and administrative positions related to Cincinnati Milacron's electronic controls and robots work since he joined the company in 1964.

He has been associated with the industrial robots division since its inception in 1977. Most recently he served as its manager of research and development.

Radke holds a bachelor's degree in electrical engineering from the University of Cincinnati. He is a member of the board of directors of the Robot Institute of America.

Automatix Completes Move

Automatix Inc., manufacturers of industrial robotics systems, has completed its move to new and larger quarters in Burlington, Mass., according to Phillipe Villers, AI's President.

The new 20,000 square-foot site will be used for combined research and development, manufacturing and administrative purposes. Interim quarters had been located in Waltham, Mass.

The recently formed company, with $6 million in capital, believes itself to be the first firm specializing in turnkey modular robotic systems for industrial use.

AI's first three systems are "Autovision," a proprietary vision module that can provide a sense of "sight" to robot systems; "Cybervision," a system for programmable automatic assembly of small and medium-size parts for a variety of industries; and "Robovision," a system for vision-controlled arc welding.

Villers said the company is currently engaged in development of these products and anticipates first deliveries in the second half of the year.

Automatix believes intelligent robotics systems will play a major role in increasing the productivity of U.S. industry. The company sees itself as part of the emerging shift toward computer-aided manufactur-

ing to increase the efficiency and therefore the competitiveness of batch manufacturing in this country.

SME Study Forecasts Growth in CAM

Key manufacturing managers in the United States predict a greater use of computer aided manufacturing (CAM) over the next 10-20 years than do their counterparts inthe United Kingdom and Japan, according to the *Delphi Forecast of Computer Aided Manufacturing* recently released by the SME and the University of Michigan. The study compares anticipated trends in a wide range of computer aided technologies in the three countries, including CAD, CAM computer graphics, process planning, robotics numerical control (N/C, CNC, DNC), group technology and related techniques.

The study had some interesting predictions regarding the use of industrial robots in manufacturing. Although the experts predicted that by the mid 1990's twenty percent of the small batch production industry will be using programmable robots for automatic assembly, the U.S. respondents anticipated than more than half of America's small plants (under 1000 workers) would *never* use robots in their CAM operations. Surprisingly, British and Japanese forecasters said 50% of their small plants *will* be using robots by the year 2000. The study also indicated that by 1990 (1994 in U.K.), 20% of all industral machine tools sold will be designed to eliminate the need for a dedicated operator through automatic part handling and tool changing and complete computer process monitoring.

Copies of the complete study will be available about July 1 from SME's Marketing Dept. at One SME Drive, P. O. Box 930, Dearborn, MI 48128. A six page special report on the study is available from SME's Public Relations Dept.

Hohn Receives Engelberger Award

Richard E. Hohn, product manager of robotics for Cincinnati Milacron Inc., has been awarded the 1980 Joseph F. Engelberger Award of the Robot Institute of America.

The basis for the award, said RIA President Jerry Kirsch, was Hohn's project leadership in the conception and development of a robot control system using fully computerized logic and communications. Kirsh said Hohn's innovations have changed the way robots move, simplified their programming, adapted them to working environments, increased reliability and extended applications.

Hohn received the award—a commemorative medallion and a $1,000 honorarium—March 5 in Milan, Italy, at the 10th International Symposium on Industrial Robots. The presentation was made by Joseph F. Engleberger, the robotics pioneer for whom the award is named.

Hohn holds bachelor's and master's degrees in mechanical engineering from Purdue University and a master's in business administration from Xavier University.

Past award winners were Professor Yukio Hasegawa, Waseda University, Tokyo, 1977; Jerry Kirsch, president of Auto-Place Inc., Troy, Mich., 1978; and Ole Molaug, Trallfa Company, Bryne, Norway, 1979.

RIA is a trade association whose membership includes major manufacturers, distributors, research facilities and corporate users of industrial robots in the United States.

Short Course on Switched Mode Power Conversion

The educational division of TESLAco Optimum Power Conversion Inc. will conduct three-day short courses in "Switched-Mode Power Conversion: Design

(cont. page 56)

TECHNICAL ABSTRACTS

As a part of our goal of disseminating current technical information to our readers, this department will list abstracts of significant recent technical papers, in cases where these papers are available to the public. The relevant addresses will normally be listed after the abstracts. We urge academic and industrial research centers to send us abstracts of recent papers in Robotics and Artificial Intelligence for possible inclusion in this department, with appropriate prices and ordering procedures.

K-lines: A Theory of Memory, by Marvin Minsky, A.I. Memo No. 516.

Most theories of memory suggest that when we learn or memorize something, some "representation" of that something is constructed, stored and later retrieved. This raises questions like: how is information represented, how is it stored, how is it retrieved, how is it used?

This paper tries to deal with all these at once. When you get an idea and want to "remember" it, you create a "K-line" for it. When later activated, the K-line induces a partial mental state resembling the one that created it. A "partial mental state" is a subset of those mental agencies operating at one moment. This view leads to many ideas about the development, structure and physiology of Memory, and about how to implement frame-like representations in a distributed processor.

(Available from the MIT AI Lab, 545 Technology Square, Cambridge, MA 02139.)

An Image Interpretation System, by J. L. Paul, University of Sussex, This thesis describes a program which interprets, in 3-dimensional terms, pictures of a puppet in various poses. The program handles a variety of puppet constructions (as long as the body parts have parallel edges), and images produced from a variety of sources (e.g. produced from grey-level images, by hand, by a computer puppet-drawing program). The program expects the images to be noisy, so does not rely much on such traditional considerations as line junctions or line configurations, but on 'higher' concepts such as clusters of parallel lines. Several levels and kinds of intermediate structures are used, such as 'limb' regions, combinations of 'head'-'trunk' regions, 'arm' pairs, and 2.5-dimensional (i.e. overlapping laminae) puppet models. The final interpretation of the image is basically non-quantitative, and is in terms of the direction the trunk is turned (e.g. 'right', 'left'), and the degree of turn (e.g. 'slight', 'moderate', 'extreme'), the viewing angle ('down' or 'straight'), the angle of the limbs with respect to the trunk, etc. This interpretation (called a 3-D specification) is based on the 2.5-D puppet, and may be used to help specify the 3-D papameters of a 3-D puppet model which the computer can then draw.

The control of the system is non-hierarchic. The overall control structure is that of a tree search, the nodes of the tree beign either processes or 2.5-D puppets. Expanding a node is equivalent to running a process—running a process may result in the creation of new node processes. Local control is via demons—in this case, the demons are planted onto functions, and are activated when the functions are called.

(Available from: University Microfilms International, 300 N. Zeeb Road, Ann Arbor, MI 48106, Publication no. 78-11, 757.)

An Architecture For A Loosely-Coupled Parallel Processor, by Robert M. Keller, Gary Lindstrom, and Suhas Patil, Report UUCS-78-105

An architecture for a large (e.g. 1000 processor) parallel computer is presented. The processors are loosely-coupled, in the sense that communication among them is fully asynchronous, and each processor is generally not unduly delayed by any immediate need for specific data values. The network supporting this communication is tree shaped, with the individual processors connected at leaf nodes. The machine executes a graphical version of application LISP. The program execution model is demand-driven, with a special deferred interpretation for dotted pair evaluation, termed "lenient CONS". Opportunities for concurrency arise in the parallel evaluation of arguments to strict operators, i.e. those known to require evaluation of their full argument complement. Such opportunities are exploited by exporting function application tasks to neighboring nodes in the tree, subject to a hierarchical notion of load balancing. Locality of task allocation and communication is a key objective of the machine. An integrated design toward that end is presented, combining language issues, firm semantic foundation, and anticipated hardware

technologies.

(Available from the Dept. of Computer Science, University of Utah, 3160 Merrill Engineering Building, Salt Lake City, Utah 84112.)

A Computer Program For Generating The Semantics of Human Stick Figures, by Martin Herman, UMd. TR-729, MCS-76-23763.

This paper describes the current status of a computer program (SKELETON) which understands the semantics of human stick figures by making semantic inferences from the body postures and gestures of the figures. The input to the program consists of the x,y coordinates of the joints of the figures obtained from a drawing of the scene. The output is a description of what is occurring in the scene. This description takes two forms, a physical description of the configuration of each figure in three-dimensional space (e.g., FACE POINTING LEFT, KNEE2 PARTLY BENT, KNEE2 IS FORWARD), and a meaning-based description which is an interpretation of the events in the scene (eg., DEPRESSION, SADNESS, WALKING, REACHING-OUT-TO-HELP). Many parts of SKELETON are considered to be, and hence implemented in terms of, demon-driven activity. This and other details of the program are described in the paper. In addition, traces of the execution sequence of the program are displayed.

(The above reports are available from the Dept. of Computer Science, University of Maryland, College Park, MD 20742.)

Word Expert Parsing, bu Chuck Rieger and Steve Small, UMd. TR-734, NSG-7253

An approach to natural language meaning-based parsing in which the unit of linguistic knowledge is the word rather than the rewrite rule is described. In the Word Expert Parser, knowledge about language is distributed across a population of procedural experts, each representing a word of the language, and each an expert at diagnosing that word's intended usage in context. The parser is structured around a co-routine control environment in which the generator-like word experts ask questions and exchange information in coming to collective agreement on sentence meaning. The Word Expert theory is advanced as a better cognitive model of human language expertise than the traditional rule-based approach. The technical discussion is organized around examples taken from the prototype LISP system which implements parts of the theory.

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BOOKS

Principles of Artificial Intelligence, by Nils J. Nilsson, Tioga Publishing Co., Palo Alto, CA (1980). ISBN 0-935383-01, 476 pp. hardcover, $24.50.

Artificial intelligence is a two-headed beast. It consists of a small collection of general purpose, theoretically characterizable techniques (weak methods) and a large body of empirical data indicating that such methods form only a small part of an intelligent system, the far larger part consisting of techniques applicable to a particular domain. An understanding of the current state of the art of AI requires an understanding of both the science of weak methods and the art of "knowledge capturing," the process, usually *ad hoc* and hard to describe, of discovering and representing the world knowledge necessary to solve a particular set of problems. Nils Nilsson's new book, *Principles of Artificial Intelligence*, is an attempt worthy of Diderot to describe the first of these areas. Instead of concentrating on techniques used in specific problem domains within AI, it presents detailed descriptions of those general purpose methods that can be applied to problems drawn from a variety of domains.

At the beginning of the book, Nilsson argues that AI systems should be viewed as *production systems*, consisting of three components, a data base, a set of operations (productions that map from one state of the data base to another), and a control mechanism that determines which production to select next. Production systems are a way of describing *search*, the major mechanism available for solving problems for which no analytic solution techniques are known. A search problem must be formulated as a set of initial facts or situations (the starting global data base), a set of rules for deriving new facts or situations (the productions), and a set (possibly containing one element) of goals. For some problems, we define the search to have succeeded if it finds a path from the starting state to the goal. For other problems, we may demand that the search find the *best* (shortest, cheapest) path to the goal.

Nilsson describes several dichotomies that define interesting classes of production systems. One of the most important involves the type of control structure used in the system. It distinguishes between an *irrevocable* contorl strategy and a *tentative* control strategy. In an irrevocable control strategy, once a rule is selected and applied to the data base, the only thing the system can do is to select the next rule to apply to the new data base. The first rule can never be undone if it is discovered to have led down an unproductive path. This strategy is frequently easier to implement than a tentative control regime in which it is possible to undo or ignore the effects of a rule that proves to be on the wrong path. Many interesting problems can be solved effectively using an irrevocable control strategy. Such problems can be modelled as a commutative production system.

A commutative production system is a one in which application of an inference rule R to the data base never prevents application of a later rule that could have been applied just before R. In other words, useful facts can get added but never deleted. Many problem domains can be characterized by commutative produciton systems in which the system starts out with some known facts (axioms) and some rules of inference and from those can deduce additional facts (theorems). Because of this, the book devotes a great deal of attention to such systems. Two general approaches each receive an entire chapter. After a brief but very lucid introduction to first order predicate logic, the technique of *resolution* is presented. It is described both as a method for proving the validity of an assertion and as a method for extracting answers to questions such as, "For what x is it true that $P(x)$?" The basic principle behind resolution is refutation: To prove "A" prove that "not A" forms a contradiction with known facts. The next chapter is devoted to rule-based deduction systems in which the production rules provide ways to derive new theorems directly from previously known facts rather than through the refutation method used in resolution.

Despite the variety of problem areas in which commutative production systems and thus irrevocable control strategies are appropriate, there are "other problems of interest in AI [for which] the most natural formulations involve noncommutative systems. Typical problems of this sort are ones where goals are achieved by a sequence (or program) of actions. Robot problem solving and automatic programming are two domains in which these kinds of problems occur." (p. 275) In these domains the application of one rule (action) may prevent the application of other, previously applicable rules (actions).

There are two ways that tentative control strategies can be implemented. One uses backtracking, in which only one path is followed until it either succeeds or fails. If it fails the system backs up and

tries another path. A very general backtrack procedure is presented. Because of the inefficiency that frequently occurs in backtracking (the system may explore several paths to the same place since it does not remember nodes on paths it abandons), a more flexible graph search procedure is frequently called for. In such a procedure all nodes and paths are remembered and some set of control rules determines which paths should be pursued at each point in time. The search ends when any path reaches the goal. Several general graph search algorithms are presented along with some mathematical results about their effectiveness.

At this point, it becomes useful to consider another of the basic dichotomies in the world of production systems. A system is *decomposable* if "the initial database can be decompoosed or split into separate compnents that can be processed independently." (p. 37) For example, suppose we want to achieve the goal (A and B). If the system is decomposable, we can tackle the two subgoals A and B separately and combine the solutions to provide a solution to our initial goal. One chapter in the book is devoted to algorithms for searching the AND/OR graphs produced by such decomposable systems.

Unfortunately, just as many interesting problem domains, such as robot problem solving, cannot be characterized by commutative systems, many cannot be made decomposable. Again suppose that we want to achieve (A and B). We must be careful that the solution we propose for B does not undo the effect of the solution we find for A and vice versa. Two chapters of the book are devoted to strategies for dealing with problems such as this. One of the main difficulties that such systems must face is known as the *frame problem*—how can we state succinctly for each rule what parts of the global data base are changed by the rule and what parts are left unchanged. Some mechanisms for solving this problem are presented. The discussion is heavily influenced by the STRIPS problem solving system created by Nilsson and his colleagues as part of the SRI "SHAKEY" robot system.

The book concludes with a discussion of alternative ways to represent the data bases operated on by the production systems. Throughout the bulk of the book, knowledge was represented as well-formed formulae in the predicate calculus. In this capter, a brief introduction to two other representations "units," (record-like objects having fields filled with values) and "semantic networks", is provided.

Several comments can be made about the book as a whole. Its major emphasis is on the accurate mathematical treatment of the techniques it presents. Thus, it deals extensively with the mathematical process of matching potential rules against the data base to check for applicability. In presenting the methods it describes the details of applying techniques to small understandable problems rather than outlining their application to larger problems. For example, the main problems considered throughout the two chapters on robot problem solving involve the task of moving three blocks on a table into some specified configuration. Although such problems may seem trivial, they serve to illustrate many of the fundamental difficulties encountered when machines are programmed to perform tasks that humans take for granted. The book is primarily concerned with methods that can be guaranteed to find a solution if one exists, with less emphasis on how long it takes to do so, rather than with more *ad hoc* methods that may miss some solutions but can be expected to find many solutions fairly quickly.

This last remark brings us back to my opening observation. Although the book provides a thorough catalog of general, formalizable techniques that work regardless of the specific knowledge they are given, it contains little advice on how to program specialized domain-specific techniques into an AI system. Those new to the field will find an excellent introduction to domain-independent methods. However, as a guide to building practical intelligent systems, the book will be of use primarily to those who already have some exposure to the types of problems encountered in such systems and the kinds of knowledge such systems need. Without this background, some readers may find it hard to sort the many details into a more global framework.

—Reviewed by Elaine Rich

Prof. Rich is a member of the Computer Science faculty at the University of Texas at Austin.

and Measurement" at three locations this summer.

The dates and locations will be July 23-25 in Costa Mesa, California; August 26-28 in Boston; and September 15-17 in Palo Alto, California.

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USRS Opens Palo Alto Office

The United States Robotics Society recently settled in to its new communications center in Palo Alto, Calif., after a move that has been the cause of the delays in its response to inquiries.

The three-year-old society was formed to monitor and record the progress of robotics and artificial intelligence. Late last year USRS directors decided to establish a new communications center, as part of their desire to become "a major society."

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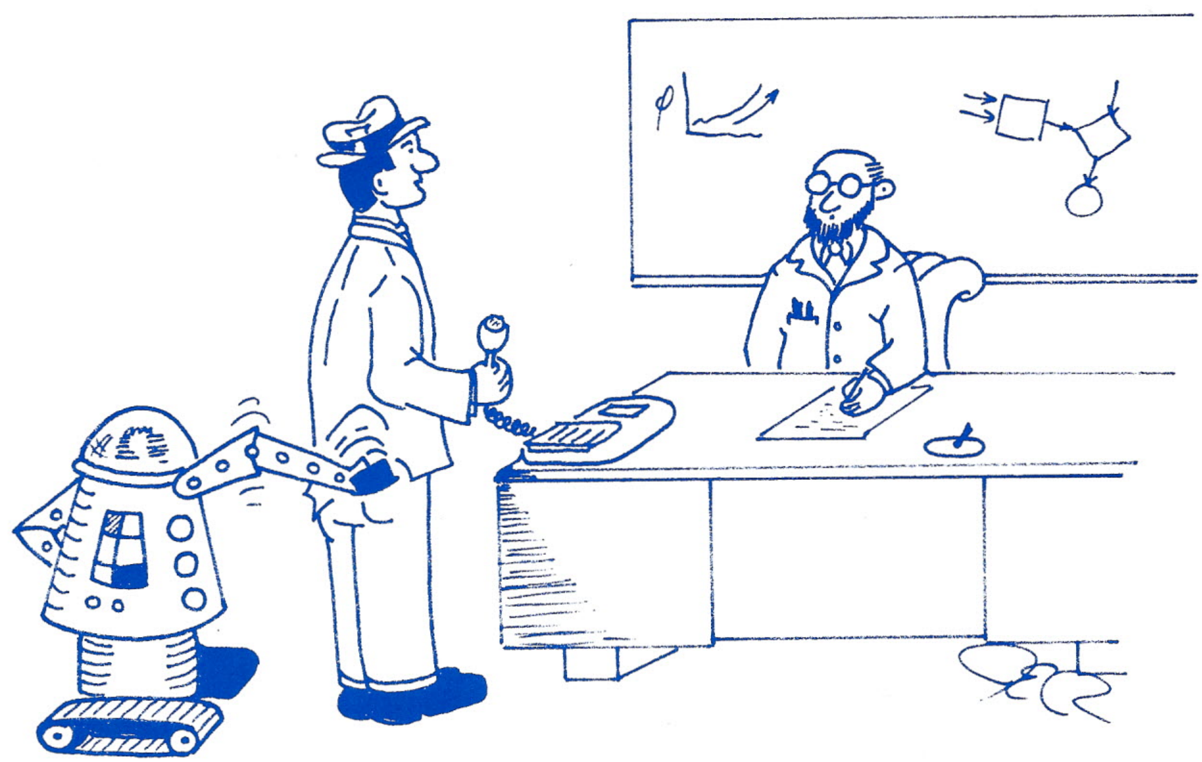

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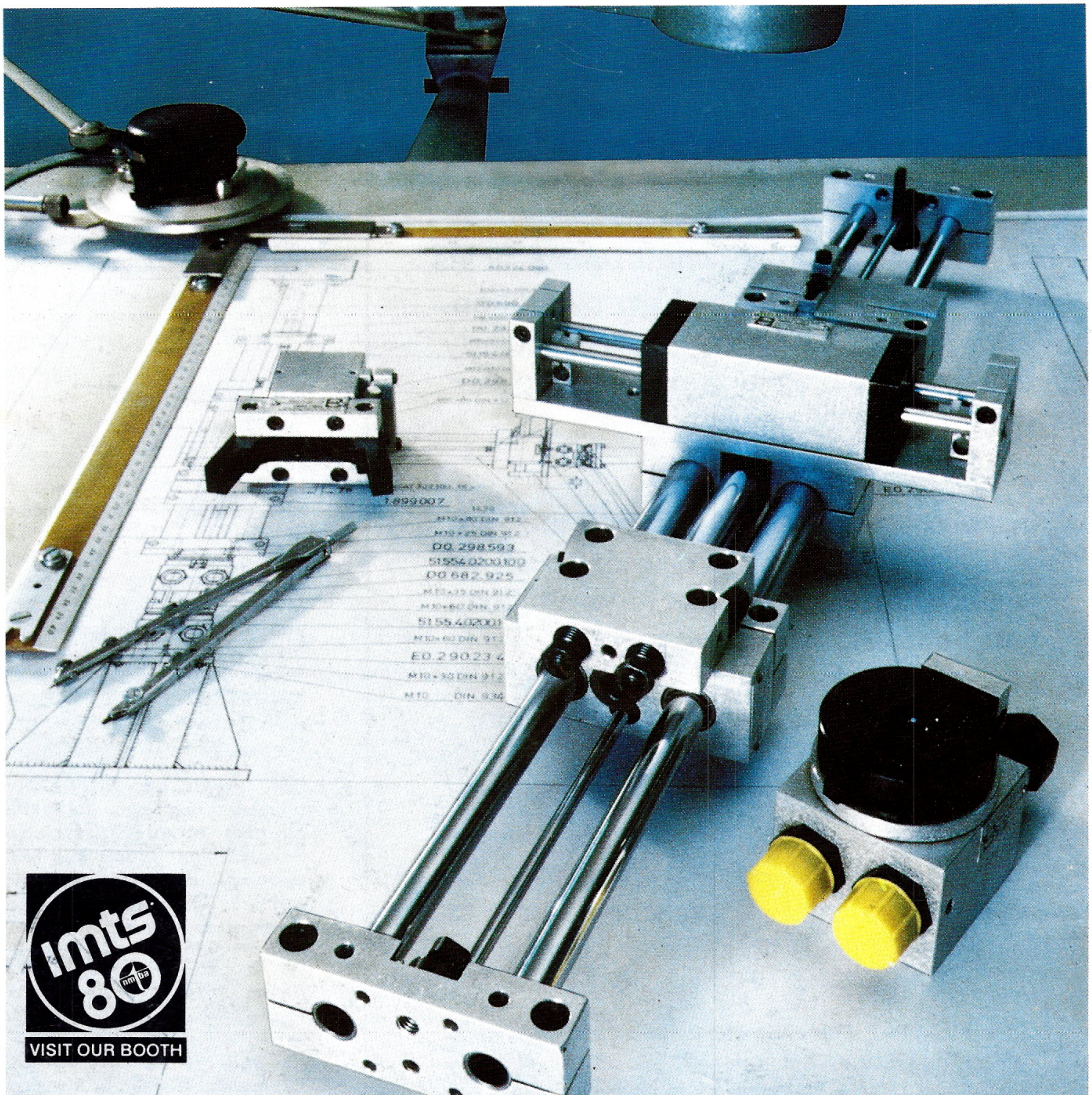

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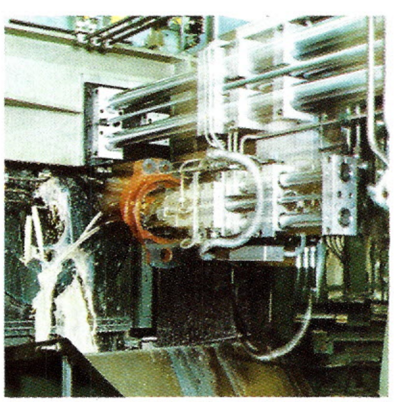

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